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Ordovician successions in southern-central Xizang (Tibet), China — refining the stratigraphy of the Himalayan and Lhasa terranes

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Abstract

The Ordovician stratigraphy of southern-central Xizang (Tibet) has been revised based on new conodont data recovered from 43 samples in four stratigraphic units and their integration with existing nautiloid and graptolite data. The *Histiodella* *holodentata* and *Pygodus serra* biozones have been identified respectively in the Alai and Jiaqu formations of the Chiatsun Group exposed near Alai village in Nyalam County within the Himalayan terrane, and the *Yangtzeplacognathus foliaceus* Subbiozone (lower part of the *Pygodus serra* Biozone) in the Sangqu Formation exposed at the Guyu section within Zayu County in the Lhasa terrane. Recognition of these biozones has increased the precision of correlation of the middle-upper Darriwilian strata in the region. Regional reassessment of the Ordovician stratigraphy permitted by new biostratigraphic data has allowed revised definitions for the Chiatsun and Keerduo groups and the Sangqu and Xainza formations. The Chiatsun Group is defined herein to include three lithologically distinctive formations in descending order, the Jiaqu, the Alai and the Adang formations. The stratigraphic age for the Jiaqu and Alai formations in the type area ranges from the middle Darriwilian (*Histiodella holodentata* Biozone) to middle Katian (*Hamarodus brevirameus* Biozone), but the age of the Adang Formation remains less certain.

Keywords Ordovician, Conodont biostratigraphy, Chiatsun Group, Keerduo Group, Sangqu Formation, Tibet

1. Introduction

Conodonts of Darriwilian (late Middle Ordovician) age reported herein were collected by four of the authors (Zhang, Fang, Yu and Li) during an expedition conducted by the Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences in 2016 (Fig. 1). Conodont samples are mainly from the Jiaqu, Alai and Hongshantou formations at two localities in Nyalam County within the Himalayan terrane in southern Xizang. Several spot samples were also collected from the correlative Sangqu Formation at the Guyu section in Zayu County within the Lhasa terrane in central Xizang and from the “Sangqu Formation” of the Haitongbingzhan section in Markam within the Qiangtang terrane of north-eastern Xizang.

Due to its remoteness, high altitude and the geographic extent of this vast mountainous region, most of the paleontological work being conducted in southern-central Xizang is of a reconnaissance nature. Ordovician conodonts from the Chiatsun Group of the Himalayan terrane were first reported briefly by Harris et al. (1987), who recovered a small conodont fauna representing the *Pygodus serra* Biozone (upper Darriwilian) from the upper part of the Chiatsun Group (= Jiaqu Formation) exposed along the east side of the road between Yagru-Xongla Pass and Nyalam (ca. 24 to 25 km from Nyalam County town). Subsequently Qiu (1988) recorded a diverse conodont fauna of Darriwilian to Katian age from the Jiaqu Formation and the conformably underlying Alai Formation exposed at a section south of Alai village in Nyalam County. Other groups of fossils reported from the Chiatsun Group include brachiopods (Liu, 1976, 1979; Harper et al., 2011; Zhan et al., 2014), crinoids (Mu and Wu, 1975; Donovan et al., 2012), nautiloids (Chen J.Y., 1975; Chen T.E., 1983, 1984; Chen J.Y. and Zou, 1984), trilobites (Qian, 1976; Zhou and Zhen, 2008), and gastropods (Yu, 1975).

Conodonts of Darriwilian to Katian age from the Lhasa terrane were previously reported from the Keerduo Group and Gangmusang Formation in a section within Xainza County (Qiu, 1988; Qu et al., 2011) and from the Sangqu Formation of Zayu County (Chen Y.H., 1985), comparable to those reported from the Himalayan terrane. Macrofossils including trilobites, graptolites, brachiopods and nautiloids were also recorded from various Ordovician units in the Lhasa terrane (Lai, 1982; Rong and Xu, 1987; Li, 1988; Qu et al., 2004; Fang et al., 2018).

In this study we report the *Histiodella holodentata* Biozone in the Alai Formation, the *Pygodus serra* Biozone in the lower part of the Jiaqu Formation and the *Yangtzeplacognathus foliaceus* Subbiozone (lower part of the *Pygodus serra* Biozone) in the Sangqu Formation. However, age determination for the Hongshantou Formation is less precise due to the lack of diagnostic species recovered from the current samples (Table 1). Precise ages for these stratigraphic units are especially significant in improving our understanding of Ordovician stratigraphy within the Himalayan and Lhasa terranes and associated arc-basin systems. These new data have also shed light on the Ordovician depositional and tectonostratigraphical history of the region, indicating paleobiogeographical ties with other parts of eastern Gondwana and peri-Gondwana, particularly with South China, North China and Western Australia (e.g., Canning Basin) during the Middle Ordovician.

2. Regional geological settings

The Qinghai-Xizang Plateau (Fig. 1), so-called the "Roof of the World", is the largest and highest plateau on Earth, with an average elevation exceeding 4,500 m and covering an area of approximately 2,600,000 km^2. With excellently exposed rocks and a complicated geological history, the plateau is an ideal natural laboratory, providing a unique window to explore the history of the Earth. Research, scientific expeditions, geological mapping and mineral exploration conducted over the last several decades have generated a wealth of literature highlighted by new hypotheses and interpretations, which, although much debated, have significantly advanced our understanding of the geological evolution of the Plateau.

Comprehensive studies have been conducted by institutions and universities worldwide (e.g., Yin and Harrison, 2000; Metcalfe, 2009; Xu et al., 2012; Zhu et al., 2012, 2013) and by the China Geological Survey (e.g., Pan et al., 2012; Wang et al., 2013) in conjunction with recently completed geological maps (1:250,000). These studies have demonstrated that the Qinghai-Xizang Plateau is a mosaic of multiple orogenic systems confined by North China, South China, Tarim, and the Indian cratons (or paleo-plates) with terranes and remnants of microcontinents and arcs captured within multiple arc-basin systems. One of the most distinctive features of this immense and complicated orogenic system is that all the tectonostratigraphic provinces and their constituent subprovinces are elongated. They are arranged mainly in an E-W trending direction and confined to fault-bounded geological domains (Fig. 1), indicating strong N-S compression driven by the India–Asia collision in the Late Cretaceous–Eocene and a strong subsequent intracontinental convergence (Wang et al., 2013). Within the Gangdese–Himalaya Orogenic System occupying the most southern part of the plateau, at least three terranes, including the Himalayan, Lhasa and Baoshan terranes have been recognized (Li et al., 2010), although some authors have treated Himalayan and Lhasa terranes as a single tectonic unit (e.g., Metcalfe, 2011, 2013).

The Himalayan terrane is located along the southern margin of the Qinghai-Xizang Plateau. It includes the Himalaya mountain range and its northern slopes, now fault-bounded to the north by the Indus–Yarlung Tsangpo Suture Zone and to the south by the Main Boundary Thrust (MBT). During the Ordovician, it was part of the northern passive margin of Greater India (Torsvik et al., 2009; Gao et al., 2016; Cao et al., 2018). The most distinctive feature of the Himalayan terrane is the deposition of a nearly continuous marine-dominated Phanerozoic succession reaching 12,500 m in thickness on the pre-Ordovician metamorphic basement (Zhou et al., 2004; Wang et al., 2013).

The Lhasa terrane is now separated from the Himalayan terrane by the Indus–Yarlung–Tsangpo Suture Zone to the south and bordered by the Bangong-Nujiang Suture Zone in the north (Fig. 1). It also has a pre-Ordovician metamorphic basement, but the sporadic and less complete Paleozoic to Mesozoic rocks unconformably overlying the basement are characterized by the wider presence of multiple episodes of volcanism and subjected to further volcanic activity and deformation in the Cenozoic (Zhu et al., 2011a, 2011b, 2013; Pan et al., 2012). It possibly formed part of the passive margin off Western Australia (eastern Gondwana) during the Ordovician (Torsvik et al., 2009; Gao et al., 2016; Li et al., 2016; Cao et al., 2018).

There is a variety of hypotheses and tectonic models, many contradictories, for the geological history of the region. Fossil faunas and floras, however, have provided irrefutable evidence for the connection of the Lhasa terrane to Himalaya and Australia during most of the Paleozoic (Metcalfe, 2013; Zhu et al., 2013; Burrett et al., 2014). For instance, the Gondwanan origin of these terranes is supported by the presence of the distinctive Gondwanan *Eurydesma* (monomyarian bivalve) and *Globiella* (briachiopod) cold-water faunas and *Glossopteris* flora in the Permian successions of the Himalayan terrane and rare occurrences of *Glossopteris* in the Lhasa terrane (Xu, 1979; Wang et al., 2013). They were either exotic terranes (e.g., Lhasa terrane) in the proximity of the western margin of eastern Gondwana (off Western Australia) and rifted away after the Triassic, or were part of the current northern margin (e.g., Himalayan terrane) of the Indian plate (Yin, 1997; Yin and Harrison, 2000; Myrow et al., 2003; Xu et al., 2006; Gehrels et al., 2011; Zhu et al., 2011a, 2001b; Zhao, 2015; Li et al., 2016; Cao et al., 2018).

3. Material and sample locations

Forty-three productive spot samples with an average weight of 4 kg each were collected from four stratigraphic units in four stratigraphic sections. They were processed by using

10% acetic acid and handpicked under a stereomicroscope and yielded a total number of 1591 specimens (Fig. 2; Table 1). The conodonts recovered were rather poorly preserved with majority of them fragmentary, often fractured and opaque black with a CAI (Color Alteration Index) of 5.

The Alai section (28°22’18” N, 86°6’18” E) is located near Alai village, ca. 35 km north of Nyalam County town. Among the 29 samples collected from this section, 21 from the Alai Formation, six from the Jiaqu Formation and two from the Hongshantou Formation, yielded conodonts (Fig. 2; Table 1). The Chiatsun Group exposed at this section overlie the Rouqiecun Group muscovite schist (Fig. 3A) and consist of the Chiatsun Group of dominantly carbonates (Fig. 3B–D) and the Hongshantou Formation of calcareous and silty shales (Fig. 3E).

Four spot samples were collected from the Jiaqu Formation at the Xianqiong section (28°21’26” N, 87°10’45” E) located at Zhaxizong village, 25 km south of Tingri County town produced conodonts. The Jiaqu Formation of the Chiatsun Group is well exposed here, consisting predominantly of nodular limestone (Fig. 3F).

At the Guyu section (29°8’15” N, 97°13’36” E) located near Guyu village, 70 km north of Zayu County town, one sample from the Dolomitic Limestone Member and six samples from the Guyu Member of the Sangqu Formation yielded conodonts (Fig. 2; Table 1). The Chayu Member of the Sangqu Formation, consisting of dominantly nodular and bioclastic limestone, is exposed near a power station (Fig. 4D–F).

At the Haitongbingzhan section (29°44’19” N, 98°43’00” E) located at 20 km northeast of Markam County town, three productive samples from the “Sangqu Formation” in the Qiangtang terrane yielded only a few specimens of poorly preserved *Panderodus* sp. (Fig. 2; Table 1). Rocks lithologically comparable to the three members (Dolomitic Limestone, Chayu and Guyu members) of the Sangqu Formation of the Lhasa terrane are well exposed along the national highway (Fig. 4A–C).

4. Ordovician Stratigraphy of the Himalayan terrane in southern Xizang

The Ordovician-Devonian marine successions in the Himalayan terrane of southern Xizang were first discovered during expeditions organized by the Chinese Academy of Sciences (1966-1968) and associated stratigraphic and paleontological investigations. Ordovician rocks in this region are exposed within several narrowly confined E-W extending tracts on the northern side of the Himalaya Mountains with its southernmost extension forming the caps on the summits of Mount Jolmo Lungma (Mount Everest) and Mount Changtse to its immediate north (Gansser, 1964; Yin, 1974, 1987; Yin and Kuo, 1978; Sheng, 1980; Wang et al., 2013; Zhan et al., 2014, Fig. 1). Mu et al. (1973) established the Chiatsun Group to include the carbonate succession cropping out in the vicinities of the uninhabited Jiacun village within Nyalam County located farther west of Mount Jolmo Lungma. However, inconsistencies in the subsequent usage and nomenclature of this stratigraphic unit (Chiatsun Group) and its constituent formations have often caused confusion and complications in stratigraphic correlation and interpretation of the regional geology and depositional history. Revision of the lithostratigraphy of these units, in their type areas and the attempt to establish a unified and well-defined stratigraphic hierarchy presented herein will be the first step to clarify their regional relationships (Fig. 5).

4.1. Hongshantou Formation

The Hongshantou Formation was named by Mu et al. (1973) for the brown shale conformably overlying the Chiatsun Group. At the type locality (coincident with that of the Chiatsun Group; see Wang 1974, 1987), it consists of brownish-red, silty and calcareous mudstone and shale of ca. 70 m in total thickness. As only the rare appearance of nautiloids has been recorded (e.g., *Michelinoceras* spp.; see Chen, 1984, p. 456), the precise geological age of the Hongshantou Formation is still uncertain. However, based on the age determinations of the underlying Jiaqu Formation (upper Darriwilian to middle Katian) and the overlying Shiqipo Formation, which yielded a diverse Llandovery graptolite fauna from the black shale in the lower part (Mu et al., 1986), the Hongshantou Formation has been considered late Katian to Hirnantian age. In this study, two samples were collected from the lower part of this formation at the Alai section (Fig. 2). They yielded a small conodont fauna. It includes *Dapsilodus* sp., *Protopanderodus nogamii*, *Protopanderodus varicostatus* and *Scabbardella* sp., broadly indicating a latest Middle Ordovician to Late Ordovician age (Fig. 2).

4.2. Chiatsun Group

Mu et al. (1973, fig. 2) defined the Chiatsun Group, with its type section exposed continuously from Jiacun village to Alai (mistakenly referred to as Yali, see Chen, 1984, p. 456) village, north of Nyalam County town; it was subdivided into the Upper Formation consisting of pinkish limestones of 97 m in total thickness and the Lower Formation of gray limestones intercalated with siltstone. At the type locality, it conformably underlies the Hongshantou Formation and attains a total thickness of over 726 m (Fig. 2, Jiacun-Alai section). Regionally it has a measurable thickness varying from 300 to 1500 m and is also exposed farther east in Yadong and Tingri counties (Fig. 1).

However, its base is rarely exposed, often found in faulted contact with the Rouqiecun Group (Wang et al., 2013, p. 21). The contact relationship between the Chiatsun Group and the Rouqiecun Group was originally considered as conformable by Mu et al. (1973) at the type localities of the Chiatsun and Rouqiecun groups, but later studies confirmed a faulted contact at both localities (Zhang, 1993; Xia, 1997).

Wang (1974) provided a more detailed lithostratigraphic description of the Chiatsun Group at its type locality, by further dividing the Lower Formation into seven lithological units (litho-units 2 to 8). Lin and Qiu (1982) proposed the Jiaqu Formation for the upper part (= Upper Formation) of the Chiatsun Group and rendered the Chiatsun Group redundant by proposing the Chiatsun Formation to replace the Lower Formation of the Chiatsun Group defined by Mu et al. (1973). Subsequently, Chen (1984) replaced the Chiatsun Group with three formations including the Quanshang Formation, which then became a junior synonym of the Jiaqu Formation erected by Lin and Qiu (1982), the Alai Formation (= litho-units 8 and 7 of Wang, 1974) and the underlying Chiatsun Formation (litho-units 6 to 2 of Wang, 1974 at the type section) (Figs 2, 5).

In this contribution, the Chiatsun Group remains as a valid stratigraphic unit representing the un-deformed Ordovician carbonate succession exposed in southern Xizang. However, the tripartite subdivision of the Chiatsun Group proposed by Chen (1984) is revised. At its type locality, the three constituent formations can be easily distinguished from each other by their distinctive and mappable lithological characters. Thus, the name Chiatsun Formation, a junior homonym of the Chiatsun Group, should be discarded. Consequently, the Adang Formation (after the abandoned Adang village near the type section of the Chiatsun Group, coordinates: 28°22’57.5769” N, 86°6’27.5256” E) is proposed herein to represent this stratigraphic unit with its upper boundary defined by the last major occurrence of the siliciclastics in the succession and its basal boundary marked by the STDS (South Tibetan Detachment System) (Figs 2, 5). The Adang Formation is characterized by a mixed lithology of carbonates and siliciclastics (mainly as siltstone and sandstone interlayers) occupying the lower part of the Chiatsun Group. In Burang and Zanda counties, a predominantly quartzite succession consisting of the Dabalao and Xialazi formations is believed to be the age equivalents of the Chiatsun Group (Wang et al., 2013), but lack supporting fossil evidence.

4.2.1. Jiaqu Formation

Lin and Qiu (1982) erected the Jiaqu Formation to replace the Upper Formation of the Chiatsun Group defined by Mu et al. (1973), with its type section ca. 50 m farther east from the type section of the Chiatsun Group. The Jiaqu Formation has a wider distribution than the other formations in the group with the maximum thickness reaching nearly 100 m; it also crops out in Dinggye and Tingri counties (Chen, 1984). The first Ordovician conodonts in the region were reported from a single sample collected from the Jiaqu Formation at a roadside outcrop exposed along the 318 National Road between Yagru-Xongla Pass and Nyalam (Harris et al., 1987). It represented a small fauna including *Cornuodus* sp. cf. *C. longibasis*, *Dapsilodus*? *similaris*, *Drepanoistodus* spp., *Drepanodus arcuatus*, *Panderodus* sp., *Periodon* sp. cf. *P. aculeatus*, *Protopanderodus varicostatus* and *Pygodus serra*.

In the following year, Qiu (1988) reported a conodont fauna from its type section exposed south of Alai village (originally referred to as Yali, but Chen, 1984, p. 456, indicated that it should be Alai) in Nyalam County; here the formation is condensed with a total recorded thickness of 33 m. Based on the occurrence of conodont species

Protopanderods liripipus and *Hamarodus brevirameus* from the purple-brownish, thinly-bedded argillaceous limestone near the top, *Amorphognathus tvaerensis* from the middle part, *Yangtzeplacognathus jianyeensis* from the bioclastic limestone in the middle-lower part, and *Yangtzeplacognathus foliaceus* from the argillaceous limestone near the base, the age of the formation ranges from the *Pygodus serra* Biozone (upper Darriwilian) to the *H. brevirameus* Biozone (middle Katian) (Figs 5–6).

The age of the basal Jiaqu Formation is also confirmed by the occurrence of *Pygodus serra* in one of our current samples from the Jiaqu Formation at the Alai section (Fig. 2). However, the Jiaqu Formation is thinner at the Alai section, ca. 21.6 m in total thickness. It yielded a small fauna of late Darriwilian age (the *Pygodus serra* Biozone) including *Dapsilodus* sp. (Fig. 7N, P–Q), *Drepanodus arcuatus* (Fig. 8D), *Eoplacognathus* sp., *Oistodus venustus* (Fig. 8H), *Protopanderodus nogamii, Protopanderodus varicostatus* (Fig. 9J), *Pygodus serra* (Fig. 9A–D), *Scabbardella* sp. and *Yangtzeplacognathus foliaceus* (Fig. 9G–H). The lack of a Late Ordovician conodont fauna at this section suggests that the Jiaqu Formation is incomplete (with its upper part missing) and might be in faulted contact with the overlying Hongshantou Formation. A small conodont fauna including *Ansella jemtlandica* (Fig. 7E), *Drepanodus* sp. (Fig. 8C), *Drepanoistodus* sp. (Fig. 7M), *Coelocerodontus* sp., Gen. et sp. indet. (Fig. 8F), *Panderodus gracilis*, *Periodon* sp. (Fig. 8M), and *Protopanderodus varicostatus* (Fig. 9K) was also recovered from four samples in the Jiaqu Formation at the Xianqiong section (Figs 1, 3F), but no age-diagnostic species were found. Cephalopods are the most common macrofossils found in the Jiaqu Formation, including *Sinoceras chinense*, *Michelinoceras elongatum*, *Archigeisonoceras elegatum* and *Troedssonella nyalamensis* (Fig. 10G–I; Chen T.E., 1984). Many of these taxa are age diagnostic and also reported from the Sandbian–Katian of South China and the Lhasa terrane, e.g., the Pagoda and Gangmusang formations (Chen

T.E. and Zou, 1984; Chen T.E., 1986; Cheng et al., 2005; Fang et al., 2018).

At the type locality for the Chiatsun Group (exposed on the eastern slope of Liangquan, ca. 1 km SE of Alai village), Chen TE (1984) proposed the Quanshang Formation to replace the Upper Formation of the Chiatsun Group, defined by Mu et al. (1973) and by Wang (1974; = litho-unit 9); it consists of purple-brownish, medium to thick-bedded limestone and marlstone of ca. 60 m in total thickness. Apparently, the Quanshang Formation is a junior synonym of the Jiaqu Formation. The Goulongri Formation was erected in the explanatory notes for the 1:100,000 Xigazê-Yadong Geological Map (1983), and is also widely used, mostly by the regional geologists for this stratigraphic unit in their geological maps and reports (Zhang, 1993; Zhou et al., 2004; Wang et al., 2013). It represents litho-unit 9 of Wang (1974) with the type locality the same as that of the Chiatsun Group (Jiacun-Alai section exposed between Jiacun and Alai villages). Therefore, it is considered a junior synonym of the Jiaqu Formation.

4.2.2. Alai Formation

The Alai Formation was established by Chen (1984) to represent the dark-gray or grayish medium to thick-bedded nautiloid limestone in the upper part of the Lower Formation of the Chiatsun Group that was recognized by Mu et al. (1973) and Wang (1974). Chen (1984) included litho-units 8 and 7 of Wang (1974) in the Alai Formation at its type locality (ca. one km SW of Alai village) in Nyalam County. However, based on Wang (1974, p. 27) litho-unit 7 consists of 118 m of gray limestone intercalated with thin-bedded siltstone, and thus should belong to the Lower Formation (= Adang Formation herein). Therefore, the Alai Formation is restricted herein to include only the medium to thick-bedded limestone of litho-unit 8 of Wang (1974) with a total thickness of 131 m at the type locality, and to have its base immediately above the highest occurrence of siliciclastic interlayer in litho-unit 7 (Wang 1974). The Alai Formation crops out only in the vicinity of Jiacun, northern Nyalam, where it is conformable with the overlying Jiaqu Formation and the underlying Adang Formation of the Chiatsun Group.

Qiu (1988) reported a small conodont assemblage from the top of this formation (at its type section) exposed south of Alai, including *Amorphognathus variabilis*, *Histiodella serrata*, *Juanognathus* sp. aff. *J. variabilis*, *Drepanodus homocurvatus*, *Paroistodus numarcuatus*, *Acodus* sp. and *Panderodus gracilis*?. Based mainly on the presence of *Lenodus variabilis* and *Histiodella serrata*, Qiu (1988, table 1) suggested an early Darriwilian age for the top part of the Alai Formation. However, the only specimen she illustrated (Qiu 1988, pl. 6, fig. 15) as *L. variabilis* is in our opinion an indeterminable fragment, and the specimen illustrated (Qiu 1988, pl. 4, fig. 18) as *H. serrata* is assigned herein to *Histiodella kristinae*, which indicates a middle Darriwilian age (the *Histiodella kristinae* Biozone, Figs 5–6). Based on brachiopods and unpublished conodont data, Harper et al. (2011) and Donovan et al. (2012) correlated the top part of this formation (Collection TNJ 014), with the *Pygodus serra* Biozone (upper Darriwilian). Conodonts representing the *Histiodella holodentata* Biozone have also been recovered from this formation at the Alai section (Figs 2, 8I–K). Therefore, the upper and middle parts of the Alai Formation are probably of Darriwilian age (the *Pygodus serra* to *H. holodentata* biozones). However, the precise age of the Alai Formation in its basal part is still uncertain. Nautiloids from the litho-unit 8 of Wang (1974) are characterized by the presence of *Dideroceras* and *Paradnatoceras yaliense* (fauna 3 of Chen 1984), suggesting an approximate correlation with the Kuniutan Formation (Darriwilian) in South China (Chen 1984, tables 1–2).

At the Alai section (this study), the carbonate succession below the Jiaqu Formation is rather poorly exposed, consisting of four discontinuous outcrops, separated by the soil coverage and broken rock pieces, with a total estimated thickness of ca. 762 m (Fig. 2). It is considered as belonging to the Alai Formation in the absence of siliciclastic beds. Therefore, it is difficult to rule out the possibility that the section is faulted and repeated. Conodonts recovered from the four exposures suggest a correlation: the upper part with the *Histiodella kristinae* Biozone and the lower part with the *Histiodella holodentata* Biozone (Figs 2, 6). The upper part (AGQ-30 and AGQ-29) yields *Ansella jemtlandica* (Fig. 7C), *Aurilobodus leptosomatus* (Fig. 7G–H)*, Baltoniodus* sp. (Fig. 7J), *Drepanodus* sp., *Eoplacognathus* sp., Gen. et sp. indet., *Loxodus* sp., *Panderodus* sp., *Periodon* sp., *Plectodina* sp. (Fig. 8P), *Protopanderodus cooperi* (Fig. 9P), *Protopanderodus nogamii* (Fig. 9L–O), *Protopanderodus varicostatus* (Fig. 9I) and *Scabbardella* sp. The lower part characterized by the appearance of *Histiodella holodentata* (Fig. 8I–K) yields *Amorphognathus* sp. (Fig. 7A), *Aurilobodus leptosomatus* (Fig. 7F, I)*, Baltoniodus* sp. (Fig. 7K), *Drepanodus* sp. (Fig. 8A–B), *Loxodus* sp. (Fig. 8L), *Panderodus gracilis*, *Panderodus* sp. and *Protopanderodus nogamii* (Fig. 9L–O).

Species of the nautiloid genera *Wutinoceras*, *Ordosoceras*, *Wadema*, *Pomphoceras, Ormenoceras*, *Meitanoceras* and *Armenoceras* are common in the Alai Formation, including *Pomphoceras contractum*, *Ordosoceras yaliense*, *Wutinoceras remotum*, *Wadema xizangensis* and *Meitanoceras subglobosum discoides* (Fig. 10B–F; Chen J.Y., 1975; Chen T.E., 1983). Many of these forms were also widely documented from the Machiakou Formation of North China and Lhasai Formation of the Lhasa terrane (Chen J.Y., 1976; Fang et al., 2018). Özdikmen (2008) proposed the name *Wadema* to replace *Georgina* Wade, 1977, as the latter was a junior homonym of *Georgina* Key, 1976. Species of *Wadema* were first discovered from the Middle Ordovician of the Georgina Basin in central and northern Australia (Wade, 1977). Subsequently, it was reported from the Middle Ordovician of the Himalayan terrane, the Kongur area of Xinjiang and the Kanchanaburi Province of Thailand (Chen T.E., 1983; Chen J.Y. and Wang, 1983; Stait and Burrett, 1984), suggesting a close biogeographic tie between these terranes in eastern Gondwana and peri-Gondwana (Yu et al., 2019, fig. 10).

4.2.3. Adang Formation (new name)

At its type section (the same as the Chiatsun Group; see Wang, 1974; Jiacun-Alai section, see Fig. 2), the Adang Formation of the Chiatsun Group with a total thickness of ca. 625 m, consists of medium to thick-bedded limestone intercalated with thin-bedded sandy limestone, siltstone and fine-grained sandstone intercalations in the upper part and with dolomitic limestone, siltstone and fine-grained sandstone intercalations in the lower part (=litho-units 7 to 2 of Wang, 1974). Therefore, as currently defined, the Adang Formation includes the entire Chiatsun Formation (= litho-units 6-2 of Wang, 1974) plus the lower part of the Alai Formation (= litho-unit 7 of Wang, 1974) defined by Chen (1984). At the type locality, Mu et al. (1973) and Wang (1974) believed that the Adang Formation conformably overlies the crystalline limestone of the Rouqiecun Group, but this contact relationship was confirmed to be a fault contact (Zhang 1993, p. 34).

So far, conodonts have not been recorded from this formation. Based on the nautiloid fauna, this unit was broadly correlated with Floian to Dapingian rocks in South China (e.g., Hunghuayuan Formation and at least part of the Dawan Formation) (Wang, 1974, table 3-1; Chen, 1984, table 2; Zhang, 1993). Two informal nautiloid biozones were recognized in the original Lower Formation (= Alai and Adang formations) defined by Mu et al. (1973) and Wang (1974); the lower biozone (the *Pomphoceras-Manchuroceras* biozone) was correlated with the Zhuozishan (Zotzeshan) Formation (middle Darriwilian) of the Ordos Basin in

North China on the basis of the presence of *Pomphoceras* and trilobite *Pseudocalymene* (Wang et al., 1987, p. 192). The *Pomphoceras-Manchuroceras* biozone is characterized by abundant *Pomphoceras*, and other species including *Manchuroceras* sp. and *Hopeioceras chiatsunense* (Fig. 10A; Chen J.Y., 1975). However, *Manchuroceras* was regarded as the index for the Liangjiashan Formation (Floian) of North China and Honghuayuan Formation (Floian) of South China (Chen J.Y., 1976; Xu and Xu, 1988). A more recent study of the brachiopods from the Chiatsun Group indicated that the base of the Adang Formation was no older than Dapingian (Zhan et al., 2014, fig. 4).

4.3. Rouqiecun Group

The Rouqiecun Group was designated by Mu et al. (1973) for a series of low-grade metamorphic rocks with a thickness varying from 40 to 160 m. At its type locality ca. 3 km to the northwest of Rouqiecun village in Nyalam County, it was subdivided into the Lower Formation of predominantly quartzose schist and the Upper Formation of crystalline limestone. Based on the presumed conformable contact with the overlying Chiatsun Group, radiometric age dating and regional correlation, Mu et al. (1973) considered the Upper Formation of the group Tremadocian in age (Early Ordovician) and the Lower Formation, Cambrian. They correlated the Upper Formation with the Jolmo Lungma Formation exposed on the summit, from which a U–Pb date of 410–515 Ma was obtained. Although this geological age has been accepted by many subsequent authors (Zhan et al., 2014; Dhital, 2015; Zhang et al., 2019), there is no compelling paleontological evidence from this metamorphic unit. However, a microflora from the correlative Bomi Group of the Lhasa terrane exposed in the Bomi-Zayu-Gongshan area suggested a late Neoproterozoic (Sinian) to early Cambrian age (Xie et al., 2007). Based on detrital zircon data and the regional distribution of this unit, Myrow et al. (2006a, 2006b, 2009) suggested an early-middle Cambrian age for the Rouqiecun Group and correlated it with the North Col Formation of the Jolmo Lungma region and the Parahio Formation of northern India. However, based on the zircon age and magnetic fabric of the deformation, Zou et al. (2006, 2015) suggested a Neoproterozoic age for the Rouqiecun Group. Although isotopic date for the Rouqiecun Group varies from the middle Cambrian to Neoproterozoic, it is clear that the Ordovician unmetamorphosed sedimentary cover of the Chiatsun Group exposed in the Nyalam region is separated from the underlying Rouqiecun Group by the STDS (Lu et al., 2008; Myrow et al., 2009; Zou et al., 2015; Kellett et al., 2018).

4.4. Mt Jolmo Lungma Formation

The Mt Jolmo Lungma Formation was introduced by Yin and Guo (1978, pp. 633–636; also see Yin and Guo, 1979, p. 9) for the gray fine-grained massive crystalline limestone exposed on the summit of Mount Jolmo Lungma. This name (also variably referred to as the Mount Qomolangma Formation, Mt Qomolangma Formation or Qomolangma Formation) has now been widely used, although preceded by several informal names including the Upper calcareous series (Odell, 1925), the Everest limestone (Wager, 1939; Gansser, 1964), and Mt. Everest Limestone (Gysin and Lombard, 1960). The Everest limestone (or limestones) defined by Wager (1939) includes the Mt Jolmo Lungma Formation and the underlying Yellow Band (see Gansser, 1964, p. 162). Gansser (1964, p. 163) wrote “the Everest limestone forms an erosional relic on the top part of Everest and is completely surrounded by the pelitic formation. It reappears farther to the north as a flat, north-dipping table on the Changtse Mountain”. Petrologic studies demonstrated that the limestones contained abundant fine fragments of trilobites, crinoids, ostracods and fecal pellets (Sakai et al., 2005). Wager (1939) recorded the first fossil remains (crinoids) from the summit of Mount Jolmo Lungma, but he assigned a Carboniferous-Permian age for this limestone unit. Mu et al. (1973) suggested an Early Ordovician age for the Mt Jolmo Lungma Formation and correlated it with the Upper Formation of the Rouqiecun Group based on the similarity in structural character, metamorphism and mineral constituents of these two units and a radiometric (U-Pb) age (410-515 Ma) from the Mt Jolmo Lungma Formation. Yin and Kuo (1978, 1979) considered an Early-Middle Ordovician age for this unit and correlated it with the Lower Formation (= Alai and Adang formations herein, Fig. 5) of the Chiatsun Group exposed approximately 100 km to the west in the Nyalam region. That age assignment was mainly based on the occurrence of trilobites, crinoids and brachiopods in the Mt Jolmo Lungma Formation exposed farther north ofMount Jolmo Lungma in the vicinities of Chaya, Chiuhala River and Chienchin River within Tingri County (Fig. 1). The brachiopod fauna from the Mt Jolmo Lungma Formation in these latter areas was initially documented by Liu (1979) and subsequently revised by Zhan et al. (2014), who suggested a Darriwilian age. On the summit ofMount Jolmo Lungma, the Mt Jolmo Lungma Formation is in faulted contact (Qomolangma Detachment) with the underlying Yellow Band, which gained its name by a distinctive yellowish-brown color when weathered, and consists of intercalated beds of quartzose marble, calcareous quartzose phyllite and calcareous phyllite of middle Cambrian age (Myrow et al., 2009). Therefore, the Mt Jolmo Lungma Formation with a total thickness of 225 m exposed on the summit of Mount Jolmo Lungma may correlate broadly with the lower part of the Chiatsun Group (= Adang Formation) in the Nyalam region, but is lithologically dominated by highly recrystallized massive or thick-bedded sandy limestone (Sakai et al., 2005; Myrow et al., 2009).

4.5. Kurgiakh Orogeny

A regional tectono-thermal event (Kurgiakh Orogeny), corresponding to the final episode of the pan-African Orogeny, widely affected eastern Gondwana (Kröner and Stern, 2004) and the Himalayan terrane during the late Cambrian to the earliest Ordovician (Garzanti et al., 1986; Myrow et al., 2009, 2010, 2016; Liu et al., 2015). It was responsible for the deformation (regional metamorphism) of the Rouqiecun Group and other basement rocks in southern Xizang and for the unconformity between the Ordovician cover and the underlying basement rocks in north India and Bhutan. Based on biostratigraphic data, Myrow et al. (2016, fig. 9) indicated that this regional uplift event caused a depositional hiatus spanning ca. 22 to 36 myr between the deposition of the Cambrian basement strata and the Ordovician cover of the Himalayan terrane. The timing of the Kurgiakh Orogeny is more or less coincident with those of Event 1 of the Huaiyuan Epeirogeny, the Samphire Marsh extensional event, the Delamerian Orogeny and the Third Episode of the Ross Orogeny. Event 1 of the Huaiyuan Epeirogeny with its terminal age (early Darriwilian) dated by conodonts is represented by a widely distributed disconformity between the upper Floian and middle Darriwilian strata on the North China Platform (Zhen et al., 2016). In the far western New South Wales of eastern Australia, the Delamerian Orogeny is represented by an unconformity between the middle Cambrian rocks (e.g., Gnalta Group and Ponto Group) and the overlying shallow-marine post-Delamerian rocks of latest Cambrian to Early Ordovician age (Greenfield et al., 2010), and was contemporaneous with the Episode 3 of the Ross Orogeny in Antarctica (Zhen et al., 2019, fig. 3). The Samphire Marsh extensional event initiated extension and deposition of the Canning Basin in Western Australia (Shaw et al., 1994; Hashimoto et al., 2018). Recent studies in the Canning Basin (Normore et al., 2018; Zhen et al., 2018) suggested a terminal age of late Tremadocian (dated by conodonts and U–Pb zircon age) for the Samphire Marsh extensional event in the Canning Basin.

5. Ordovician Stratigraphy of the Lhasa terrane in central Xizang

In the Lhasa terrane, Ordovician rocks are exposed mainly in two widely separated areas, the Xainza and Zayu regions (Fig. 1).

5.1. Xainza region

In this area, Ordovician rocks are exposed mainly inXiongmei and Zhaqu, Xainza County (Fig. 1). The Lower Ordovician (Zhakang and Taduo formations) consists of weakly to moderately metamorphosed siliciclastic rocks (siltstone, sandstone and conglomerate) with minor crystalline limestone interbeds with a total thickness of ca. 680 m (Fig. 11). It is conformably overlain by a carbonate succession (Keerduo Group) with a maximum thickness of 485 m (Wang et al., 2013, p. 32), ranging in age from Middle Ordovician to Late Ordovician (middle Katian). The Gangmusang and Xainza formations are characterized by the intercalation of shales and thin-bedded or nodular limestones deposited during a major transgression in the region and in lithological transition with the underlying Keerduo Group and conformably overlain by Silurian graptolitic black shales of the Dewukaxia Formation.

5.1.1. Xainza Formation

The discovery of the *Hirnantia* fauna and the youngest Ordovician graptolite fauna in the top part of the Gangmusang Formation promoted Ni et al. (1981) and Lin (1981) to split and name this part of the unit as the Xainza Formation, representing the uppermost Ordovician exposed in the Xainza area of central Xizang. At its type section located at Gangmusang, 10 km south of the Yongzhu Bridge in the Xainza County, it has a total thickness of 14.09 m; it consists of 5.2 m of yellowish calcareous or silty graptolitic mudstone in the lower part and 8.82 m dark-gray muddy limestone bearing a shelly fauna (brachiopods and trilobites) in the upper part (Ni et al., 1981). Examination of the graptolites from the Xainza Formation at Riajue and Zhiwazuogu sections in Xainza by one (YDZ) of the authors confirms the occurrence of *Normalograptus* cf. *extraordinarius* (Fig. 12E), *N. ojsuensis* (Fig. 12B, D), *Diplograptus temalaensis* (Fig. 12C) and *Neodiplograptus charis* (Fig. 12F) indicating a Hirnantian age (Ni et al., 1981). Based on the diverse graptolite fauna represented by more than 20 species from the lower part, and the *Hirnantia* fauna from the upper part of the Xainza Formation, Ni et al. (1981) correlated the lower part of the Xainza Formation with the top part of the Wufeng Formation (*Diplograptus bohemicus* Biozone), and the upper part with the Kuanyinchiao Bed of South China. They considered the Ordovician/Silurian boundary coincided with the boundary between the Xainza Formation and the overlying Dewukaxia Formation. Although the original definition provided by Ni et al. (1981), has been accepted by the majority of subsequent workers (e.g., Chen T.E., 1986; Xia, 1997; Wang et al., 2014; Zhang et al., 2019), Lin (1983) restricted the Xainza Formation to the calcareous shale in the lower part of the formation defined by Ni et al. (1981). He coined the term Riajiaoabuduo Formation for the muddy limestone bearing the *Hirnantia* fauna, which was equivalent to the upper part of the Xainza Formation defined by Ni et al. (1981). However, due to its minimal thickness (varying from only 14 to less than 2.5 m) and difficulties surrounding its recognition in the field, other authors have abandoned the Xainza Formation and included it either at the top of the Gangmusang Formation (Zhang et al.,

2004) or in the basal part of the Dewukaxia Formation (Shi and Wang, 1999; Qu et al., 2004, 2011).

Although it is lithologically transitional between the Dewukaxia and Gangmusang formations, the Xainza Formation is retained here as a valid lithostratigraphic unit. It consists of the upper dark-gray muddy limestone and calcareous mudstone and lower yellowish calcareous or silty graptolitic mudstone, lying conformably between the graptolitic black shale of the Dewukaxia Formation and the carbonates of the Gangmusang Formation. Therefore, the litho-unit 7 of 1.74 m thick of the dark gray-yellowish calcareous mudstone with muddy limestone interlayers, originally taken as the base of the Dewukaxia Formation by Ni et al. (1981) at its type section, is included in the underlying Xainza Formation. Thus, the Ordovician/Silurian boundary is now within the revised Xainza Formation (Fig. 11).

5.1.2. Gangmusang Formation

The Gangmusang Formation was defined by the Geological Survey Team of the Xizang Bureau of Geology and Mineral Resources (1980; also see Xia, 1983), as consisting of lower calcareous shale with sandy and calcareous nodules and thinly-bedded limestone and bioclastic limestone interbeds, the middle gray-dark gray mud striped limestone with bioclastic limestone and minor shale interlayers and the upper medium-thick-bedded limestone intercalated with sandy and mud-striped limestone. At its type section located at Gangmusang, 5 km south of the Yongzhu Bridge and ca. 50 km north of Xainza County town, it has a total thickness of 479.55 m and is in conformable contact with the underlying Keerduo Group and the overlying lower Silurian Dewukaxia Formation, graptolitic black shale with gray-black, thinly-bedded limestone interbeds. Qiu (1988, pl. 6, fig. 22a–b) reported the presence of *Amorphognathus superbus* from the lower part of the Gangmusang Formation, which had a known stratigraphic range of middle Katian in Baltoscandia (Männik and Viira, 2012; Ferretti et al., 2014; Zhen and Percival, 2017). The Gangmusang Formation yields abundant nautiloids, including *Michelinoceras huangnigangense*, which is the characteristic fossil for the Huangnigang and Linxiang formations in South China, *Michelinoceras variabilum*, also occurring in the Pupiao Formation in Baoshan of western Yunnan, and *Pleurothoceras* also reported from the Bull Fork Formation (Richmondian: Upper Ordovician) in Ohio, USA (Chen T.E., 1986).

5.1.3. Keerduo Group

The Keerduo Group was originally proposed by Xia (1979) in an unpublished manuscript and was formally introduced into the literature by the Geological Survey Team of the Xizang Bureau of Geology and Mineral Resources (1980; also see Shi and Wang, 1999) for the carbonate succession conformably underlying the Gangmusang Formation. However, Xia (1983, figs 1, 3) formally published this unit as the Keerduo Formation, which has been widely accepted by most Chinese workers (Xia, 1997; Wang et al., 2014). At its type locality on Keerduo Mountain, it conformably underlies the Gangmusang Formation, but its base is unexposed, and consists of the upper, thinly-bedded gray limestone (with clay mud striped limestone and bioclastic limestone in the lower part), and the lower thin to thick-bedded purple-grayish-green clay, mud striped limestone has a measured thickness of 250 m. We follow the original definition provided by the Xizang Regional Exploration Team of the Geological Bureau (1980) to apply the term Keerduo Group to the carbonate-dominated succession conformably overlying the Zhakang Formation and underlying the Gangmusang Formation. It can be subdivided into three formations, i.e., the Zhiwazuogu Formation (new name proposed herein after the Zhiwazuogu Hill located in the vicinity, with coordinates: 31°9'27.9288"N, 88°43'47.4996"E) for the thinly-bedded gray limestone with clay mud striped limestone and bioclastic limestone of the upper Keerduo Formation defined by Xia, 1983) with a total thickness of 139 m at its type locality; the Xungmei Formation (=thin to thick-bedded purple-grayish-green mud striped limestone of the lower Keerduo Formation defined by Xia, 1983); and the Lhasai Formation forming the lower part.

Chen T.E. (1986) proposed the Xungmei Formation for the purple-red and yellow-gray mud-stripped limestone or nodular limestone exposed in Riajiao hill and the southern hill, ca. 30 km north of Xainza. It is equivalent to the lower Keerduo Formation defined by Xia (1983) (see Fig. 11). Zhang et al. (2003) established the Lhasai Formation for the carbonate succession exposed in Lhasai and the vicinity of Xiongmei, Xainza County, characterized by the occurrence of a distinctive *Actinoceras* fauna, which they believed to be of Early Ordovician age. Graptolites including *Aulograptus climacograptoides*, *Nicholsonograptus* sp. and *Pterograptus* sp. from the Lhasai Formation in Xainza suggest an early to middle Darriwilian age (Fig. 12I). Fang et al. (2018) recently studied the nautiloid fauna, suggesting a Middle Ordovician (most probably Darriwilian) age. Apart from bearing a distinctive nautiloid fauna, the Lhasai Formation is distinguished lithologically from the overlying Xungmei Formation by its gray-dark gray color of thin to medium-bedded bioclastic limestone.

Lin (1983) and Qiu (1988) reported the occurrence of the conodont *Pygodus anserinus* from the Xungmei Formation, but the only illustrated specimen of *P. anserinus*, by Qiu (1988, pl. 6, fig. 14) was in our opinion an undiagnostic Pb element. Qiu (1988) recognized the *Hamarodus brevirameus* Biozone from the Zhiwazuogu Formation of the Keerduo Group at its type locality. Nautiloids are common in the Keerduo Group, represented by the species of *Pomphoceras*, *Wutinoceras*, *Mesowutinoceras*, *Armenoceras*, *Deiroceras globosom* and *Discoactinoceras* in the lower part and *Sinoceras*, *Michelinoceras*, *Lituites*, *Trocholites* and *Discoceras* in the upper part (see Chen T.E., 1986; Fang et al., 2018). Therefore, based on conodonts and nautiloids, the Keerduo Group has an age ranging from at least Darriwilian to middle Katian, and correlates with the Chiatsun Group of the Himalayan terrane (Fig. 6).

5.1.4. Zhakang Formation

The Zhakang Formation was established by Zhang et al. (2004; also see Cheng et al., 2005) for the weakly to moderately metamorphosed succession consisting in the lower part of siltstone and fine sandstone and in the upper part of quartzitic sandstone and slate with a combined thickness of ca. 263 m. At its type locality, it is in a conformable relationship with the overlying nautiloid limestone (Keerduo Group) and the underlying Taduo Formation. The occurrence of *Tetragraptus approximatus* (Fig. 12H), *T. scandens* Ruedemann, *Didymograptellus protoindentus* (Fig. 12A), *D. eobifidus* (Fig. 12 G), *Dichograptus octobrachiatus*, *Expansograptus opimus*, and trilobites from near the base of Zhakang Formation provided an accurate age (earliest Floian) for its base (Cheng et al., 2001; Zhang Y.C. et al., 2004; Cheng et al., 2005, fig. 3).

5.1.5. Taduo Formation

At its type locality in Zhakang, Taerma area, Xainza County, the Taduo Formation has a total thickness of ca. 401 m and unconformably overlies the Precambrian metamorphics (schist and phyllite). It consists of a basal quartzitic conglomerate, lower quartzite, middle siltstone and sandy mudstone with minor crystalline limestone interbeds and the upper crystalline limestone intercalated with mudstone and siltstone (Zhang et al., 2004; Cheng et al., 2005). The unit is weakly to moderately metamorphosed and the only fossils found were trilobite fragments in the upper part. Based on its conformable contact relationship with the Lower Ordovician Zhakang Formation, Zhang et al. (2004) suggested that this unit was Tremadocian in age and might possibly extend downwards into the Cambrian (Figs 6, 11).

5.2. Zayu region

In this area, the Ordovician System is a carbonate-dominated succession but represented only by a few small isolated outcrops (Fig. 1).

5.2.1. Lajiunong Formation

At the type section of the Guyu Formation (considered herein as the Guyu Member of the Sangqu Formation), Chen et al. (1986) recognized an unnamed dolostone and dolomitic limestone unit of ca. 40 m in thickness, between the underlying Guyu Member of the purple-reddish mud-striped limestone and the overlying Silurian? cherty shale, siltstone, slate and phyllite (Chen et al., 1995). Wang et al. (2013, p. 40) formally named it the Lajiunong Formation. Based on the conformable contact with the underlying Sangqu Formation and the unconformable contact with the overlying Silurian? rocks, it was considered of Late Ordovician age; but no fossils have been recorded from this dolostone unit (Fig. 6).

5.2.2. Sangqu Formation

Chen B.W. et al. (1982) named the Sangqu Formation with the type section crossing the Sangqu River, south of Guyu Town in Zayu County, where it is in faulted contact with the Guqin Group (= Bomi Group) of Neoproterozoic–early Cambrian age and conformably overlain by Lower Devonian red beds. At the type locality it is composed of basal brecciated limestone, dolomitic limestone, limestone with cherty bands and nodular limestone with sandstone and shale interbeds in the lower part and has a total thickness of 178 m (varying from 95–217 m in the area). Subsequently, Chen et al. (1986) named three Ordovician stratigraphic units in the same area (in Guyu, Zayu County), including (in ascending order) the Gujin Group (>150 m thick in the type section with unexposed lower part), the Chayu Formation (25 m thick purple, medium-thick bedded mud-striped limestone in the type section) and the Guyu Formation (25 m thick gray, medium-thick bedded mud-striped limestone in the type section). The Gujin Group included the dolomitic limestone (or dolostone) in the upper part and siliciclastics (shale, sandstone and quartzite) in the lower part. The Guyu and Chayu formations were defined on the basis of their medium to thick-bedded, mud-striped limestones, and differentiated from each other by the purple-red color of the former and gray (yellow-brown when weathered) of the latter. However, the Guyu Formation, Chayu Formation and the upper part of the Gujin Group are equivalent to the upper, middle and lower parts of the Sangqu Formation. Therefore, they are revised herein as three consecutive members of the Sangqu Formation. The dolomitic limestone of the upper Gujin Group defined by Chen et al. (1986) is redefined here as the lower member of the Sangqu Formation, and formally named as the Dolomitic Limestone Member (new name) with a total thickness of 98 m at its type locality. The siliciclastics (shale, sandstone and quartzite) of the lower part of the Gujin Group originally defined by Chen et al. (1986) (Fig. 11) should correlate to the Guqin Group (see following discussion).

The conodont fauna represented by both *Pygodus serra* and *Yangtzeplacognathus foliaceus* was recovered from the top bed (Litho-unit 10) of the Sangqu Formation, indicating a correlation with the *Pygodus serra* Biozone (upper Darriwilian) (Chen Y.H., 1985). This age determination has also been confirmed by the same fauna characterized by the appearance of *Yangtzeplacognathus foliaceus* in one of our current samples from the upper part of the Sangqu Formation (Fig. 9F). One sample from the Dolomitic Limestone Member of the Sangqu Formation in this study (AGQ-13) yielded a few poorly preserved specimens of *Panderodus* sp., which are undiagnostic for age determination.

5.2.3. Guqin Group (= *Bomi Group*)

The Guqin Group was proposed by Chen B.W. et al. (1982) for the weakly to moderately metamorphosed siliciclastics-dominated succession underlying the Sangqu Formation, exposed in the vicinity of Gujin (mistakenly spelt as Guqin by these authors). At its type section (crossing the Sangqu River south of Guyu Town in Zayu County) measured by Chen B.W. et al. (1982, fig. 3), it is over 1000 m in exposed thickness (base unexposed) and consists of sandstone and mudstone with minor interlayers of limestone and volcanics (metamorphosed as schist and marble). Chen B.W. et al. (1982) considered it was in conformable contact with the overlying Sangqu Formation and suggested a pre-Ordovician age for the Guqin Group; they correlated it with the Rouqiecun Group of the Himalayan terrane. More recent studies have confirmed that the Sangqu Formation is in faulted contact with the underlying Guqin Group of the Neoproterozoic-Cambrian age (Xie et al., 2007). The Xizang Bureau of Geology and Mineral Resources (1997) treated the Guqin Group as a junior synonym of the Nianqingtangula Group, the latter consisting of high-grade metamorphics (predominantly gneiss and marble). However, Wang et al.

(2013) posited a Precambrian age for the Nianqingtangula Group based on radiometric age dates.

Both the Gujin Group and Bomi Group, subsequently used in the region, are junior synonyms of the Guqin Group. The Gujin Group was proposed by Chen et al. (1986) to accommodate the carbonates (dolomitic limestone and dolostone) and siliciclastics (shale, sandstone and quartzite) conformably underlying the Chayu Formation (= Chayu Member of the Sangqu Formation herein). At its type locality (at Gujin, Guyu, in Zayu County), it has a exposed thickness of 148 m. The upper part of the Group consisting of 98 m of carbonates, is correlated with the Dolomitic Limestone Member of the Sangqu Formation (Figs 6, 11). The lower part of the Gujin Group consists of siliciclastics (>50 m in total exposed thickness at the type locality) as originally defined by Chen et al. (1986) and lack of fossils. It is lithologically comparable with the Guqin Group.

Zhu and Dang (1993) established the Bomi Group for the succession of metamorphosed sandstone, schist, marble and volcanics exposed in Bomi, Chayu County and recorded a diverse microflora (36 species) from its upper part. However, at its type locality, the Bomi Group has an exposed thickness of 96.3 m with its contact relationships with the underlying and overlying rocks obscured by a granitic intrusion and Quaternary cover at the base and top respectively. Subsequently Xie et al. (2007, fig. 3) reported a total thickness of 1612 m for this group exposed in Yajiu at Guyu, Chayu County and a diverse microflora from the Bomi Group in the Bomi-Zayu-Gongshan area represented by some 50 species, which suggest a Neoproterozoic to early Cambrian age.

6. Conodont biostratigraphic summary of the Chiatsun Group and regional correlation

The conodonts reported from the Chiatsun Group (although limited to only three publications: Harris et al., 1987; Qiu, 1988; this study) provide crucial data for its age, recognizing four conodont biozones (the *Pygodus serra*, the *Yangtzeplacognathus jianyeensis*, the *Amorphognathus tvaerensis*, and the *Hamarodus brevirameus* biozones) in the Jiaqu Formation, and two biozones (the *Histiodella holodentata* and the *H. kristinae* biozones) in the Alai Formation. They suggest a late Darriwilian to middle Katian age for the Jiaqu Formation and a middle-late Darriwilian age for the underlying Alai Formation.

6.1. Histiodella holodentata Biozone

A number of samples from the Alai Formation in the Alai section (Fig. 2) yielded *Histiodella holodentata*, a cosmopolitan species widely distributed in deeper water settings. Its appearance in the Alai Formation provides a direct correlation of this stratigraphical interval within the Alai Formation with the *H. holodentata* Biozone recognized in three major Chinese terranes (South and North China and Tarim), Australia, Sibumasu, Argentine Precordillera, North America and Europe.

6.2. Histiodella kristinae Biozone

The only record of *Histiodella kristinae* in this region is a specimen illustrated by Qiu (1988, pl. 4, fig. 18) as *Histiodella serrata* from the top part of the Alai Formation at the type locality of the Jiaqu Formation in southern Xizang. Its occurrence provides direct correlation of the top Alai Formation with the *H. kristinae* Biozone, widely recognized in South China, Australia, Tarim Basin, North America and Europe. It was a cosmopolitan species widely distributed in deeper water settings (e.g., outer-shelf and slope-basin), and can correlate to the *Eoplacognathus suecicus* Biozone recognized in the Baltoscandian succession and also in the Jiangnan Slope of South China (Wang et al., 2019, fig. 1). In Australia, *H. kristinae* has only been recorded from deep-water, slope-basin successions of the Lachlan Orogen in central NSW (Percival and Zhen, unpublished material) (Fig. 6).

6.3. Pygodus serra Biozone

Harris et al. (1987, pl.2, figs M, N, R) reported a *Pygodus serra* fauna from the Jiaqu Formation exposed on the roadside ca. 24 to 25 km north of Nyalam County town. *Eoplacognathus suecicus* (see Qiu, 1988, pl. 4, figs 3–5, 13–14) and *Yangtzeplacognathus foliaceus* (see Qiu, 1988, pl. 4, figs 7–8) were recovered from the lower member (member A) of the Jiaqu Formation (type section) south of Alai village in Nyalam County. Co-occurrence of both species suggests a correlation with the basal part of the *P. serra* Biozone (= the *Y. foliaceus* Subbiozone) of the Baltoscandian conodont succession (Zhang, 1998c; Bergström and Ferretti, 2017) and the South China succession (Wang et al., 2019). In the Alai section (this study), both *Pygodus serra* (Fig. 9A–D) and *Y. foliaceus* (Fig. 9G–H) were recovered from the Jiaqu Formation.

In the Lhasa terrane, both *Y. foliaceus* and *P. serra* were recorded from the top of the Sangqu Formation in the Guyu section (exposed on roadside ca. one km south of Guyu town) of the Zayu County (Chen et al., 1986; Fig. 9F). Recognition of the *Pygodus serra* Biozone (upper Darriwilian) in the upper part of the Sangqu Formation confirms its direct correlation with the lower part of the Jiaqu and upper part of the

Alai Formation of southern Xizang (Fig. 6).

The nautiloid faunas from the Guyu Member (*Richardsonoceras asiaticus, Michelinoceras paraelongatum*, *M. elongatum* and *Sinoceras* sp.) and from the Chayu Member (?*Dedirocerass* sp. and *Protocycloceras* sp.) can be closely compared with those from the Jiaqu Formation of southern Xizang and the Keerduo Group in Xainza region of the Lhasa terrane and from Middle Ordovician (Kuniutan and upper Dawan formations) in South China, respectively (Chen et al., 1986; Chen et al., 1996; Qu et al., 2004).

6.4. Yangtzeplacognathus jianyeensis Biozone

An and Ding (1982) and An (1987) named and established the *Yangtzeplacognathus jianyeensis* Biozone to represent a stratigraphical interval now correlated with the *Baltoniodus variabilis* Biozone and the upper part of the *Yangtzeplacognathus jianyeensis-Pygodus anserinus* Biozone in South China (Wang et al., 2019, fig. 1). The type specimens of this species are from the Datianba Formation in the Waiyugou section of Tangshan, Jiangning, Jiangsu Province, where it co-occurs with *Pygodus anserinus* (see Wang, 1993, p. 22). Based on the material from Hunan, Zhang (1998a, 1998b) revised this species in detail and proposed the *Y. jianyeensis-P. anserinus* Biozone, to correlate with the *P. anserinus* Biozone of the Baltoscandian succession. Subsequent studies revealed that *Y. jianyeensis*, as a morphologically distinctive species, had a wide distribution. Therefore, having a well-known stratigraphic range, it is used as a biozone index species by itself (when *P. anserinus* is absent in the shallower water deposits) or along with *P. anserinus* to define the Middle/Upper Ordovician boundary interval. In the three stratigraphical sections in Hunan studied by Zhang (1998a), both *Y. jianyeensis* and *P. anserinus* have the same stratigraphic range with their first appearances in the same stratigraphic horizon. It is thus a range biozone defined by the FAD as the base and LAD as the top by *Y. jianyeensis* and/or *P. anserinus* (Wang et al., 2019).

Qiu (1988, pl. 4, figs 7–9) reported *Y. jianyeensis* from the middle member (member B) of the Jiacun Formation at its type locality, which secures direct correlation with the *Y. jianyeensis*-*P. anserinus* Biozone (uppermost Darriwilian-lower Sandbian) of the Yangtze Platform. The occurrence of *P. anserinus* from the Xungmei Formation exposed in Xainza County within the Lhasa terrane cannot be confirmed since the only specimen Qiu (1988, pl. 6, fig.14) illustrated was a Pb element. Wang C.Y. (in Qu et al. 2004, 2011, p. 17, table 2–3) also recorded the occurrence of *Y. jianyeensis* near the base of the Zhiwazuogu Formation in the Keerduo Group, supporting the age assignment for the lower part of this unit (Fig. 6). Therefore, the lower part of the Zhiwazuogu Formation of the Keerduo Group correlates with the middle part of the Jiaqu Formation (Fig. 6).

6.5. Amorphognathus tvaerensis Biozone

The *Amorphognathus tvaerensis* Biozone (subdivided further into the *Baltoniodus alobatus*, the *B. gerdae* and the *B. variabilis* subbiozones) was originally established for the stratigraphical interval (= most of the Sandbian and basal Katian) between the *Pygodus anserinus* Biozone and the *Amorphognathus superbus* Biozone in the Baltoscandian conodont succession (Bergström, 1971, 1983; Bergström and Ferretti, 2017, fig. 5). Subsequently this biozone was either modified to include four subbiozones (e.g., Bergström and Leslie, 2010) or substituted by four or five biozones (e.g., Männik and Viira, 2012). However, as demonstrated by Männik and Viira (2012, fig. 2), the eponymous species of the *B. variabilis* Biozone that directly overlies the *P. anserinus* Biozone, makes its first appearance in the lower part of the *P. anserinus* Biozone. Consequently, the base of the *B. variabilis* Biozone (or the lowest subbiozone of the *A. tvaerensis* Biozone) is defined by the FAD of *A. tvaerensis*, which extends to the upper part of the *B. alobatus* Biozone (upper Sandbian) in Baltoscandia. *Amorphognathus tvaerensis* has only been reported from the Datianba Formation in Anhui (Ding et al. in Wang, 1993; Wang et al., 2011) and Hunan (Fang et al., 2019) in South China and in the Jiaqu Formation in southern Xizang (Qiu, 1988). Based on the occurrence of *A. tvaerensis* in Anhui, Ding et al. (in Wang, 1993) established the *A. tvaerensis* Biozone in the upper part of the Datianba Formation for the stratigraphic interval between the *Baltoniodus variabilis* Biozone and the *Amorphognathus superbus* Biozone in the Lower Yangtze Valley of South China. Apparently this biozone, only recognized in Anhui, correlates with the upper part of the *A. tvaerensis* Biozone in the Baltoscandian conodont succession and the *B. alobatus* Biozone recognized on the Yangtze Platform (Wang et al., 2018a, 2019; Fig. 6). In the Jiaqu Formation (type section), Qiu (1988, pl. 6, figs 4–13) recorded *Amorphognathus tvaerensis* from the lower part (litho-unit 3) of the upper member (member c). However, the resolution of the conodont succession recognized in the Jiaqu Formation in southern Xizang is relatively low, and the *Amorphognathus tvaerensis* Biozone represents a stratigraphical interval (extending through most of the Sandbian to lowermost Katian) between the overlying *Hamarodus brevirameus* Biozone (middle Katian) and the *Yangtzeplacognathus jianyeensis* Biozone (lowermost Sandbian to highest Darriwilian) (Fig. 6).

Qiu (1988, pl. 6, fig. 22) suggested an early Katian age (the *Amorphognathus* *superbus* Biozone) for the Gangmusang Formation exposed in Xainza of the Lhasa terrane, but the only specimen she illustrated as *A. superbus* is incomplete and poorly preserved that cannot be confidently assigned, even to generic level. Moreover, Qiu (1988) suggested a middle Katian age (the *Hamarodus brevirameus* Biozone) for the upper part (Zhiwazuogu Formation) of the underlying Keerduo Group. If this age determination is correct, the conformably overlying Gangmusang Formation should be younger (Fig. 6). Therefore, based on the conformable contact with the underlying Keerduo Group, the Gangmusang Formation is broadly correlated with the Hongshantou Formation of the Nyalam region in southern Xizang (Fig. 6).

6.6. *Hamarodus brevirameus Biozone*

In South China, the conodont succession documents the Upper Ordovician *Hamarodus brevirameus* Biozone that represents the middle Katian interval, with its eponymous species widely reported in the Pagoda Formation of the Yangtze Platform and also from the top part of the Yenwashan Formation of the Jiangnan Slope (An, 1987; Wang et al., 2011, 2019; Zhang et al., 2019). In the type section of the Jiaqu Formation (see Zhang, 1993), Qiu (1988; Fig. 2) divided this unit into three informal members consisting of five beds, and recorded *H. brevirameus* from the upper part of the member C (upper member, litho-units 5 and 4). Occurrence of this biozonal index species in the top of the Jiaqu Formation suggests a correlation with the *H. brevirameus* Biozone (middle Katian) in South China. Qiu (1988) also reported the appearance of *H. brevirameus* in the Zhiwazuogu Formation of the Keerduo Group exposed in Xainza of the Lhasa terrane indicating a direct correlation with the upper part of the Jiaqu Formation and the Pagoda Formation in South China (Fig. 6).

7. Conclusions

The Chiatsun Group of the Himalayan terrane is defined herein as consisting of three formations, namely the Jiaqu, Alai and the Adang formations. Six conodont biozones with ages ranging from the middle Darriwilian (the *Histiodella holodentata* Biozone) to the middle Katian (the *Hamarodus brevirameus* Biozone) are recognized in the Jiaqu and Alai formations. They provide crucial evidence for the precise correlation regionally and internationally for these two Ordovician carbonate units, but the age of the Adang Formation remains less certain.

The Keerduo Group exposed in the Xainza region of the Lhasa terrane is subdivided into the Zhiwazuogu, Xungmei and Lhasai formations. Age ranges and the stratigraphic correlation of the Keerduo Group and the conformably underlying Zhakang and overlying Gangmusang formations are assessed based on conodonts and associated graptolites and nautiloids. The Keerduo Group, ranging in age from middle Katian to at least Darriwilian in the Xaiza region and the Darriwilian Sangqu Formation in the Zayu region can approximately be correlated with, the entire or part of the Chiatsun Group of the Himalayan terrane.

Regional reassessment of the Ordovician stratigraphy in southern-central Xizang has resulted in the revised definitions of the Chiatsun Group, Keerduo Group, Sangqu Formation and the Xainza Formation and in formally naming three stratigraphic units, including the Adang Formation of the Chiatsun Group, the Zhiwazuogu Formation of the Keerduo Group and the Dolomitic Limestone Member of the Sangqu Formation. We anticipate that these new biostratigraphic and lithostratigraphic classifications of the Ordovician in southern-central Xizang will provide a significantly improved foundation for more precise stratigraphic correlation and a better understanding of temporal and spatial facies architectures of the Ordovician developed in the region.

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Captions

Figure 1. Location and simplified geological maps showing the study areas in southern-central Xizang (Tibet); A. Map of China showing collation of southern-central Xizang; B. Map of southern-central Xizang showing conodont sample locations in Nyalam-Mt. Jolmo Lungma region of the Himalayan terrane (C) and Zayu in the Lhasa terrane and Mangkang in the Qiangtang terrane (D).

Figure 2. Studied stratigraphic sections in the Himalayan terrane, including type section Jiacun-Alai section (type section of the Chiatsun Group), Alai sections and Xianqiong section, Lhasa terrane (Guyu and Zhadi sections) and Qiangtang terrane (Haitongbingzhan section), showing horizons and ranges of the selected conodont and nautiloid species; D.L.M. = Dolomitic Limestone Member, HST = Hongshantou Formation, RQC = Rouqiecun Group.

Figure 3. Field photos showing field exposures of key Ordovician stratigraphic units in southern Xizang investigated in this study. A. Rouqiecun Group, muscovite schist, Alai section; B. Adang Formation, Alai section; C. Carbonate interval in the Alai Formation, Alai section, each ledge is roughly 3.5 to 4 meters thick; D. Oncoids and cortoids from the studied carbonate interval of Alai Formation, Alai section; E. Boundary between Jiaqu and Hongshantou formations, Alai section; F. Jiaqu Formation, Xianqiong section. The hammer is 30 cm long; the coin is 2 cm in diameter; the person is 180 cm in height.

Figure 4. Field photos showing field exposures of the “Sangqu Formation” (A–C) at the Haitongbingzhan section in Markam and of the Sangqu Formation (D–F) at the Guyu section in Zayu.

Figure 5. Historical subdivision of the Chiatsun Group in the Nyalam region of the Himalayan terrane, southern Xizang (Tibet).

Figure 6. Correlation of the Ordovician System in the Himalayan and Lhasa terranes of southern-central Xizang (Tibet).

Figure 7. A–B. *Amorphognathus* sp.; **A**. ?Pb element; NIGP 171207, AGQ-27, outer-lateral view (IY330-020); **B**. Pa element, NIGP 171208, AGQ-15A, upper view (IY330-018). C–E. *Ansella jemtlandica* (Löfgren); **C**. M element, NIGP 171209, AGQ-29-4, anterior view (IY331-017); **D.** P element, NIGP 171210, AGQ-28-7, inner-lateral view (IY330-029); **E**. Sc element, NIGP 171211, AGQ-42, outer-lateral view (IY331-009). F–I. *Aurilobodus leptosomatus* An in An et al.; **F.** Sc element; NIGP 171212, AGQ-28-3, inner-

lateral view (IY331-025); G–H. Sb element; **G**. NIGP 171213, AGQ-29-2, posterior view (IY331-013); **H**. NIGP 171214, AGQ-29-2, posterior view (IY331-014); **I**. Sa element, NIGP 171215, AGQ-28-3, posterior view (IY331-026). J–K. *Baltoniodus* sp.; **J**. Pa element, NIGP 171216, AGQ-30-1(2), outer-lateral view (IY332-005); **K**. Pb element, NIGP 171217, AGQ-28-1, inner-lateral view (IY331-022). **L**. *Belodina* sp.; grandiform element, NIGP 171218, AGQ-15A, inner-lateral view (IY330-16). **M**. *Drepanoistodus* sp.; Pa element, NIGP 171219, AGQ-42, outer-lateral view (IY331-012). N–Q. *Dapsilodus* sp.; **N**. S element, NIGP 171220, AGQ-31-5(2), inner-lateral view (IY332-009); **O**. Sc element, NIGP 171221, AGQ-17, outer-lateral view (330-009); **P**. asymmetrical element, NIGP 171222, AGQ-31-3, inner-lateral view (IY332-027); **Q**. Sa element, NIGP 171223, AGQ-31-3, inner-lateral view (IY332-025). Sangqu Formation (B, L, O), Jiaqu Formation (E, M–N, P–Q), others from Alai Formation; Guyu section (B, L, O), Xianqiong section (E, M), others from Alai section. Scale bars = 100 μm.

Figure 8. A–D. *Drepanodus* sp.; A–B. Pb element; **A**, NIGP 171224, AGQ-28-12, outer-lateral view (IY330-026); **B.** NIGP 171225, AGQ-28-6, outer-lateral view (IY330-030). C–D. *Drepanodus arcuatus* Pander; Sb element; **C.** NIGP 171226, AGQ-42, outer-lateral view (IY331-010); **D.** NIGP 171227, AGQ-31-5, inner-lateral view (IY332-008). **E.** *Panderodus gracilis* (Branson and Mehl); asymmetrical element, NIGP 171228, AGQ-16, outer-lateral view (IY330-014). **F.** Gen. et sp. indet., M element, NIGP 171229, AGQ-42, posterior view (IY331-008). **G.** *Eoplacognathus* sp., Pa element, NIGP 171230, AGQ-15, upper view (IY330-019). **H.** *Oistodus venustus* Stauffer, M element, NIGP 171231, AGQ-31-5, posterior view (IY332-007). I–K. *Histiodella holodentata* Ethington and Clark; Pa element; **I.** NIGP 171232, AGQ-25, outer-lateral view (IY330-001); **J.** NIGP 171233, AGQ-28-12, outer-lateral view (IY330-024); **K.** NIGP 171234, AGQ-28-3, inner-lateral

view (IY331-024). **L.** *Loxodus* sp.; P element, NIGP 171235, AGQ-28-1, inner-lateral view (IY331-020). M–N. *Periodon* sp.; **M.** Sb element, NIGP 171236, AGQ-42, inner-lateral view (IY331-011); **N.** Pb element, NIGP 171237, AGQ-16, outer-lateral view (IY330-013). O–Q. *Plectodina* sp.; **O.** Sc element, NIGP 171238, AGQ-16, outer-lateral view (IY330-015); P–Q, Pa element; **P.** NIGP 171239, AGQ-30-1, inner-lateral view (IY332-003); **Q.** NIGP 171240, AGQ-16, outer-lateral view (IY330-012). Sangqu Formation (E, G, N, O, Q), Jiaqu Formation (C, D, F, H, M), others from Alai Formation; Guyu section (E, G, N, O, Q), Xianqiong section (C, F, M), others from Alai section. Scale bars = 100 μm.

Figure 9. A–D. *Pygodus serra* (Hadding); **A.** Pa element, NIGP 171241, AGQ-31-3, upper view (IY332-018); B–C. Pb element; **B.** NIGP 171242, AGQ-31-3, outer-lateral view (IY332-020); **C.** NIGP 171243, AGQ-31-3, outer-lateral view (IY332-021); **D.** Pa element, NIGP 171244, AGQ-31-3, upper view (IY332-019). **E.** *Scabbardella* sp.; Sa element, NIGP 171245, AGQ-31-5, lateral view (IY332-015). F–H. *Yangtzeplacognathus foliaceus* (Fåhraeus); **F.** Pb element, NIGP 171246, AGQ-16, upper view (IY330-011); **G–H.** Pb element, NIGP 171247, AGQ-31-3, g, lateral view (IY332-023), H. close-up showing reticulation surface structure. I–K. *Protopanderodus varicostatus* (Sweet and Bergström); **I.** M element, NIGP 171248, AGQ-30-1, posterior view (IY331-027); **J.** Pb element, NIGP 171249, AGQ-31-5, outer-lateral view (IY332-014); **K.** Sc element, NIGP 171250, AGQ-41, outer-lateral view (IY331-004). L–O. *Protopanderodus nogamii* (Lee, 1975); **L.** Sa element, NIGP 171251, AGQ-25, lateral view (IY330-003); **M.** Sb element, NIGP 171252, AGQ-28-1, outer-lateral view (IY331-023); N–O. Pb element; **N.** NIGP 171253, AGQ-28-12, inner-lateral view (IY330-025); **O.** NIGP 171254, AGQ-28-7, lateral view (IY330-028). **P.** *Protopanderodus cooperi* (Sweet and Bergström); Pb element, NIGP 171255,

AGQ-30-1, outer-lateral view (IY331-028). A–D, G–H and J from Jiaqu Formation in the Alai section, F from Sangqu Formation in the Guyu section and K from Jiaqu Formation in the Xianqiong section, others from Alai Formation in the Alai section. Scale bars = 100 μm.

Figure 10. Ordovician cephalopods from Himalayan terrane. **A**. *Hopeioceras chiatsunense* Chen, NIGP 71432, longitudinal section. **B**. *Pomphoceras contractum* (Chen), NIGP 22984, dorso-ventral section. **C**. *Ordosoceras yaliense* Chen, NIGP 22981, dorso-ventral section. **D**. *Wutinoceras remotum* Chen, NIGP 22982, dorso-ventral section. **E**. *Wadema xizangensis* Chen, NIGP 71626, dorso-ventral section. **F**. *Meitanoceras subglobosum discoides* Yang, NIGP 71429, dorso-ventral section. **G**. *Archigeisonoceras elegatum* Chen, NIGP 80095, dorso-ventral section. **H**. *Michelinoceras elongatum* (Yü), NIGP 80080, dorso-ventral section. **I**. *Troedssonella nyalamensis* Chen, NIGP 80093, dorso-ventral section. **J**. *Wennanoceras xizangense* Chen, NIGP 80092, dorso-ventral section. All from the Jiacun-Alai section (type section of the Chiatsun Group), A from the Adang Formation, B–F from the Alai Formation and G–J from the Jiaqu Formation. Scale bars = 1 cm.

Figure 11. Historical subdivision of the Ordovician successions in the Xainza region of the Lhasa terrane, central Xizang (Tibet).

Figure 12. Graptolites from the Zhakang, Lhasai and Xianza formations in Xainza, Xizang (Tibet), China. **A**. *Didymograptellus protoindentus* (Monsen), Zhakang Formation, Xainza, NIGP 171256, NIGP 171257 (20BS037); **B**, **D**. *Normalograptus ojsuensis* (Koren’ and Mikhailova), Xainza Formation, Riajue, Xainza, NIGP 67901, 67842; **C**. *Diplograptus temalaensis* (Jones), Xainza Formation, Riajue, Xainza, NIGP 67887; **E**. *Normalograptus*

cf. *extraordinarius* (Sobolovskaya), Xainza Formation at Zhiwazuogu, Riajue, Xainza, NIGP 67856; **F**. *Neodiplograptus charis* (Mu and Ni), Xainza Formation, at Zhiwazuogu, Riajue, Xainza, NIGP 67975; **G**. *Didymograptellus eobifidus* (Chen and Xia), Zhakang Formation in Xainza, NIGP 171258; **H**. *Tetragraptus approximatus* (Nicholson), Zhakang Formation in Xainza, NIGP 171259; **I**. *Aulograptus climacograptoides* (Bulman), in association of *Nicholsonograptus* sp. and *Pterograptus* sp., Lhasai Formation (?) in the Keerduo Group, Xainza, NIGP 171260 (215-(7); **J**. *Tetragraptus* sp., Zhakang Formation, Xainza, NIGP 171261. B–F are re-photographed after Mu and Ni (1983). Scale bars = 1 mm, except for that in (H) (= 1 cm).

Table 1. List of 43 samples and conodont species recovered from four stratigraphic sections in south-central Xizang (Tibet).

Sample	Stratigraphic unit	*Amorphognathus* sp.	*Ansella jemtlandica*	*Aurilobodus leptosomatus*	*Baltoniodus* sp.	*Belodina* sp.	*Dapsilodus* sp.	*Drepanodus acuatus*	*Drepanodus* sp.	*Drepanoistodus* sp.	*Eoplacognathus* sp.	*Histiodella holodentata*	*Loxodus* sp.	*Oistodus venustus*	*Panderodus gracilis*	*Periodon* sp.	*Plectodina* sp.	*Protopanderodus cooperi*	*Protopanderodus nogamii*	*Protopanderodus varicostatus*	*Pygodus serra*	*Scabbardella* sp.	*Yangtzeplacognathus foliaceus*	Gen. et sp. indet.	Fragments	**Total number of specimens**
Haitongbingzhan section																										
AGQ-4A	Sangqu Formation														x											5
AGQ-5	Sangqu Formation																								x	1
AGQ-6	Sangqu Formation														x											3
Guyu section																										
AGQ-13	Dolomitic Limestone M.																		x						x	3
AGQ-15	Guyu Member										x				x	x										11
AGQ-15A	Guyu Member	x				x										x										13
AGQ-16	Guyu Member														x	x	x						x			52
AGQ-17	Guyu Member						x				x															23
AGQ-17A	Guyu Member		x																				x			18
AGQ-18	Guyu Member																								x	3

(Header diagonal cell: Conodont species / Sample / Stratigraphic unit)

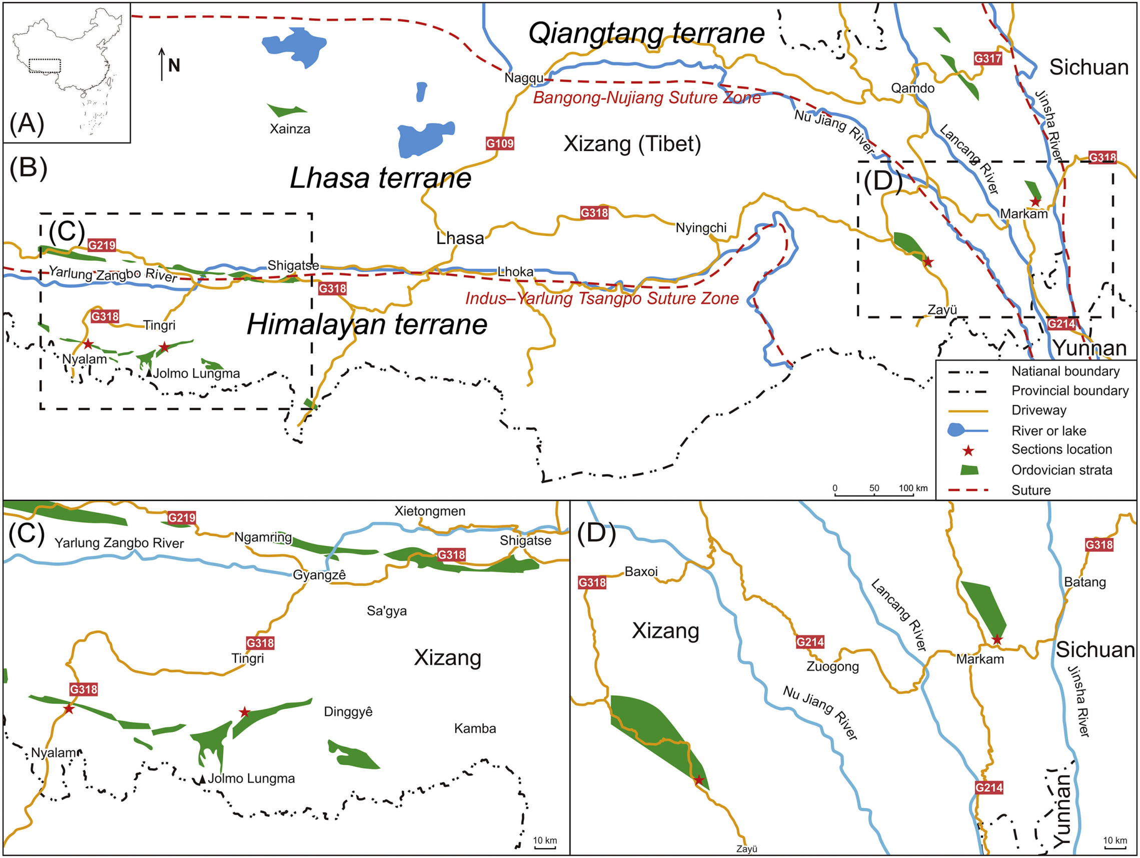
Alai section																										
AGQ-25	Alai Formation											x							x							15
AGQ-26	Alai Formation																								x	33
AGQ-27	Alai Formation	x																							x	50
AGQ-28-16	Alai Formation													x					x							20
AGQ-28-15	Alai Formation											x														36
AGQ-28-12	Alai Formation								x			x							x							53
AGQ-28-8	Alai Formation											x							x							5
AGQ-28-7	Alai Formation		x																x							18
AGQ-28-6	Alai Formation								x										x							8
AGQ-28-5	Alai Formation											x							x							44
AGQ-28-4	Alai Formation																		x							10
AGQ-28-3	Alai Formation			x								x							x							38
AGQ-28-1	Alai Formation			x	x								x						x	x						29
AGQ-29-4	Alai Formation		x					x								x			x					x		81

AGQ-29-3	Alai Formation																x							16
AGQ-29-2	Alai Formation	x															x							22
AGQ-30-5	Alai Formation																						x	32
AGQ-30-4	Alai Formation																x							6
AGQ-30-3	Alai Formation																x							8
AGQ-30-2	Alai Formation																x							32
AGQ-30-1	Alai Formation		x						x						x	x	x	x		x		x		360
AGQ-31-6	Jiaqu Formation																						x	28
AGQ-31-5	Jiaqu Formation				x	x			x			x						x		x				182
AGQ-31-4	Jiaqu Formation																						x	11
AGQ-31-3	Jiaqu Formation				x				x			x						x	x		x			116
AGQ-31-2	Jiaqu Formation																						x	101
AGQ-31-1	Jiaqu Formation																x							28
AGQ-32-2	Hongshantou Fm.				x												x	x						25
AGQ-32-1	Hongshantou Fm.																			x				26

Xianqiong section																										
AGQ-41	Jiaqu Formation																			x						7
AGQ-42	Jiaqu Formation		x					x		x						x								x		98
AGQ-43	Jiaqu Formation																								x	3
AGQ-44	Jiaqu Formation														x											6

Highlights

- Reporting new conodont data from four Ordovician stratigraphic units in southern-central Xizang (Tibet), China.
- Recognition of six conodont biozones extending from the middle Darriwilian to lower Katian in the region, which form a biostratigraphic succession for precise regional correlation of the Ordovician strata.
- Reassessment of the Ordovician regional stratigraphy and revision of definitions for four stratigraphic units, including the Chiatsun Group of the Himalayan Terrane, and the Keerduo Group and the Sangqu and Xainza formations of the Lhasa Terrane.



(A)
(B)
N
Qiangtang terrane
Sichuan
Xainza
Nagqu
Bangong-Nujiang Suture Zone
Qamdo
G317
G109
Xizang (Tibet)
Nu Jiang River
Lancang River
Jinsha River
G318
Lhasa terrane
(D)
Markam
(C)
G219
Lhasa
G318
Nyingchi
Shigatse
Yarlung Zangbo River
Lhoka
G318
Indus–Yarlung Tsangpo Suture Zone
Zayü
G318
Tingri
Himalayan terrane
G214
Yunnan
Nyalam
Jolmo Lungma
Natianal boundary
Provincial boundary
Driveway
River or lake
Sections location
Ordovician strata
Suture
0 50 100 km
(C)
G219
Xietongmen
Yarlung Zangbo River
Ngamring
Shigatse
G318
Gyangzê
Sa'gya
G318
Tingri
Xizang
G318
Dinggyê
Kamba
Nyalam
Jolmo Lungma
10 km
(D)
G318
Baxoi
G318
Batang
Lancang River
Xizang
G214
Zuogong
Markam
Sichuan
Jinsha River
Nu Jiang River
G214
Yunnan
Zayü
10 km

Figure 1

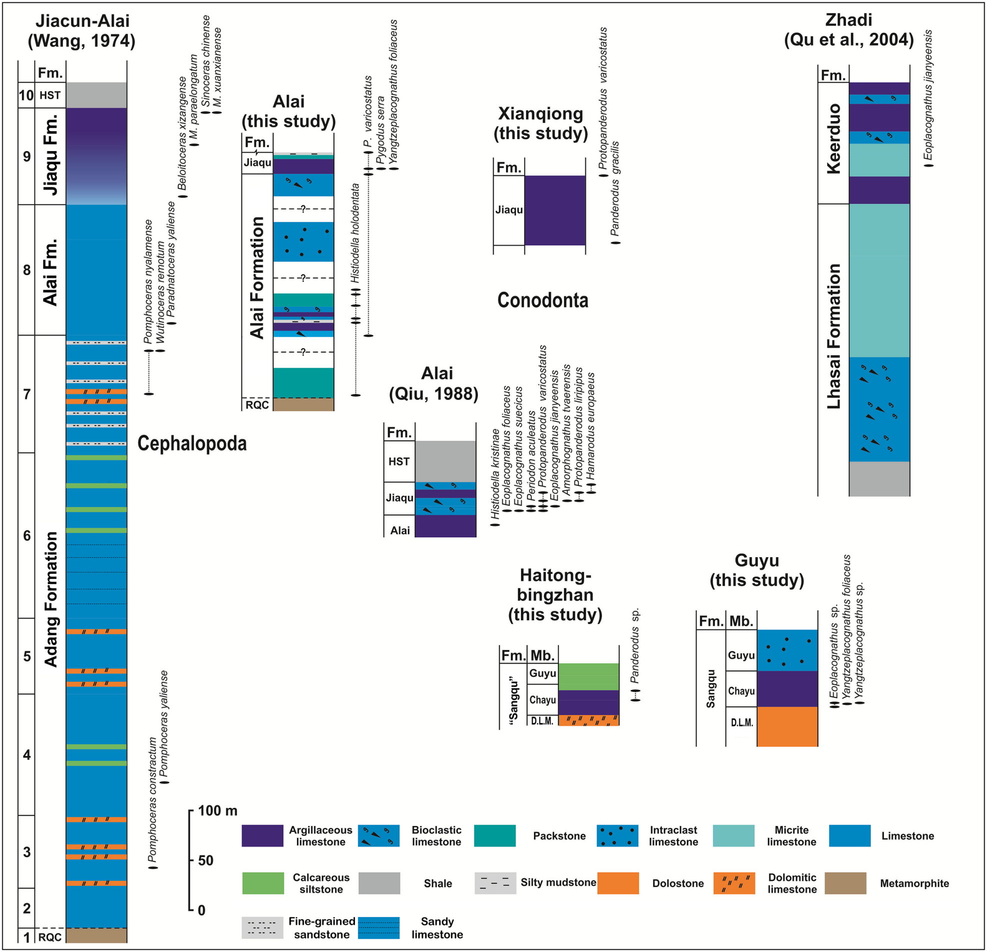

Jiacun-Alai (Wang, 1974)
Fm.
HST
Jiaqu Fm.
Alai Fm.
Adang Formation
RQC
1
2
3
4
5
6
7
8
9
10
Pomphoceras constractum
Pomphoceras yaliense
Pomphoceras nyalamense
Wutinoceras remotum
Paradnatoceras yaliense
Beloitoceras xizangense
M. paraelongatum
Sinoceras chinense
M. xuanxianense
Cephalopoda
Alai (this study)
Jiaqu
Alai Formation
RQC
Histiodella holodentata
P. varicostatus
Pygodus serra
Yangtzeplacognathus foliaceus
Xianqiong (this study)
Jiaqu
Protopanderodus varicostatus
Panderodus gracilis
Conodonta
Alai (Qiu, 1988)
HST
Alai
Histiodella kristinae
Eoplacognathus foliaceus
Eoplacognathus suecicus
Periodon aculeatus
Protopanderodus varicostatus
Eoplacognathus jianyeensis
Amorphognathus tvaerensis
Protopanderodus liripipus
Hamarodus europaeus
Zhadi (Qu et al., 2004)
Keerduo
Lhasai Formation
Eoplacognathus jianyeensis
Haitong-bingzhan (this study)
Mb.
"Sangqu"
Guyu
Chayu
D.L.M.
Panderodus sp.
Guyu (this study)
Sangqu
Eoplacognathus sp.
Yangtzeplacognathus foliaceus
Yangtzeplacognathus sp.
100 m
50
0
Argillaceous limestone
Bioclastic limestone
Packstone
Intraclast limestone
Micrite limestone
Limestone
Calcareous siltstone
Shale
Silty mudstone
Dolostone
Dolomitic limestone
Metamorphite
Fine-grained sandstone
Sandy limestone

Figure 2

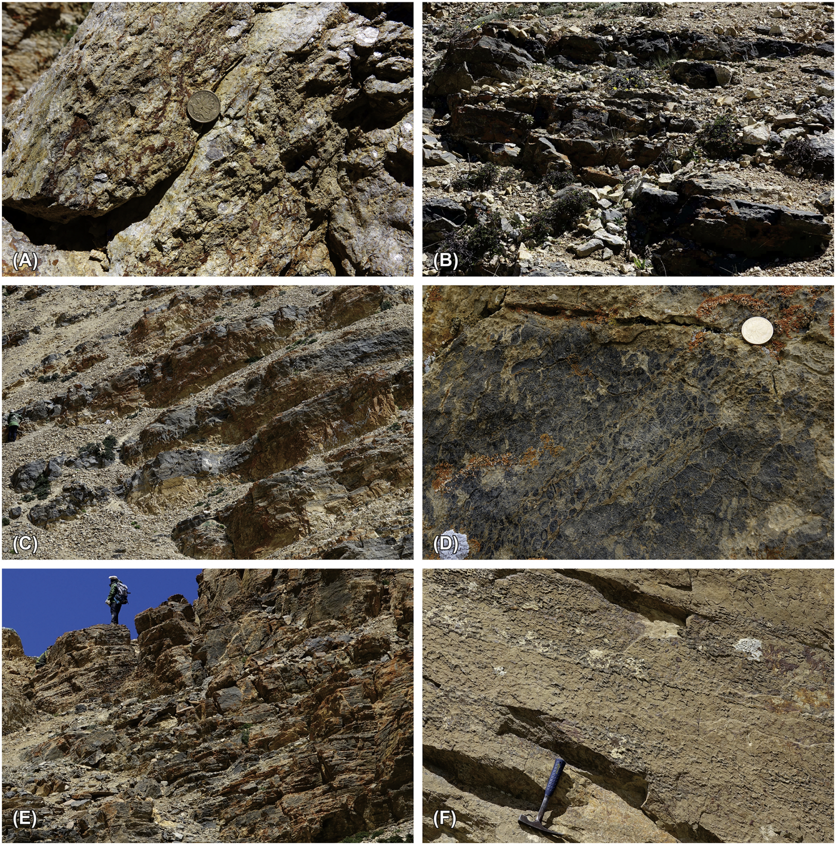


Figure 3

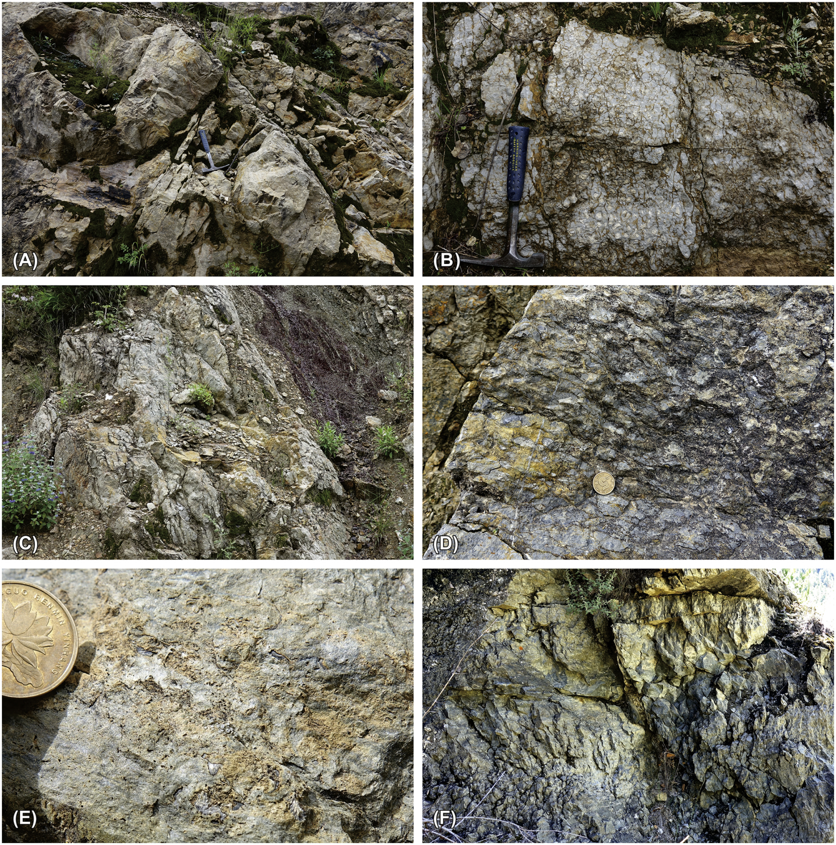


Figure 4

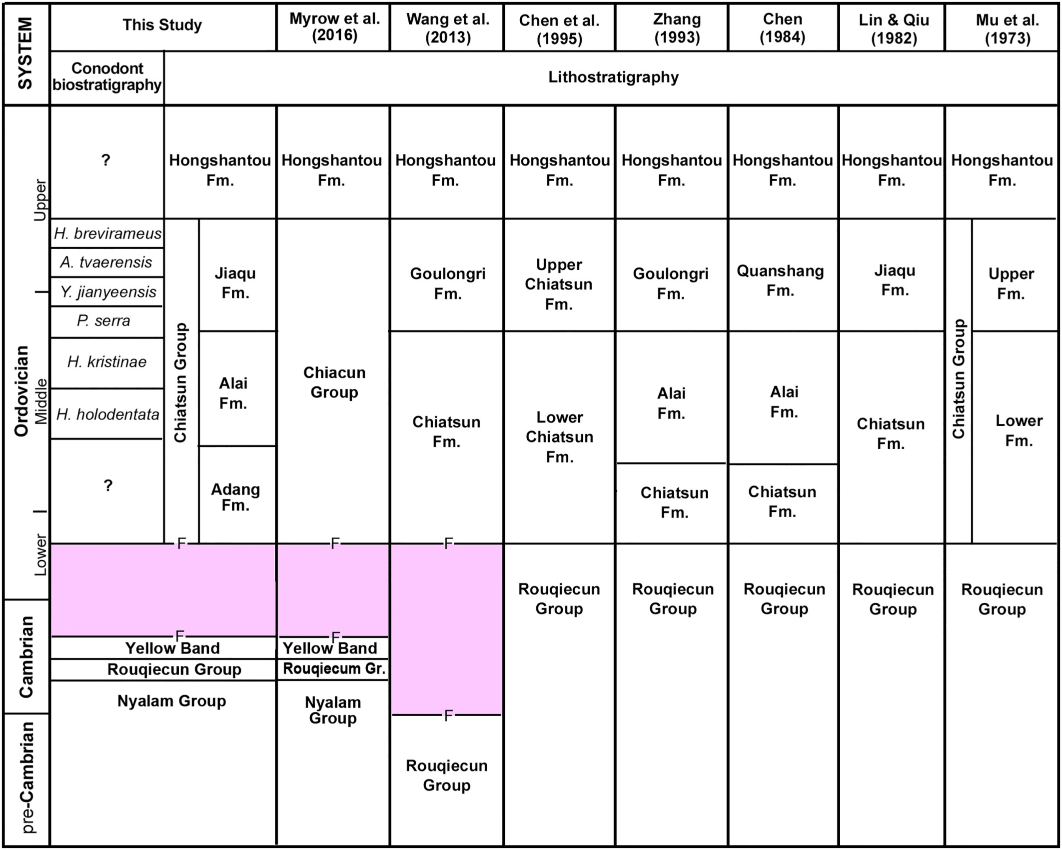

SYSTEM
This Study
Myrow et al. (2016)
Wang et al. (2013)
Chen et al. (1995)
Zhang (1993)
Chen (1984)
Lin & Qiu (1982)
Mu et al. (1973)
Conodont biostratigraphy
Lithostratigraphy
Ordovician
Upper
Middle
Lower
Cambrian
pre-Cambrian
?
H. brevirameus
A. tvaerensis
Y. jianyeensis
P. serra
H. kristinae
H. holodentata
?
Hongshantou Fm.
Chiatsun Group
Jiaqu Fm.
Alai Fm.
Adang Fm.
Chiacun Group
Goulongri Fm.
Chiatsun Fm.
Upper Chiatsun Fm.
Lower Chiatsun Fm.
Quanshang Fm.
Upper Fm.
Lower Fm.
F
Yellow Band
Rouqiecun Group
Rouqiecum Gr.
Nyalam Group

Figure 5

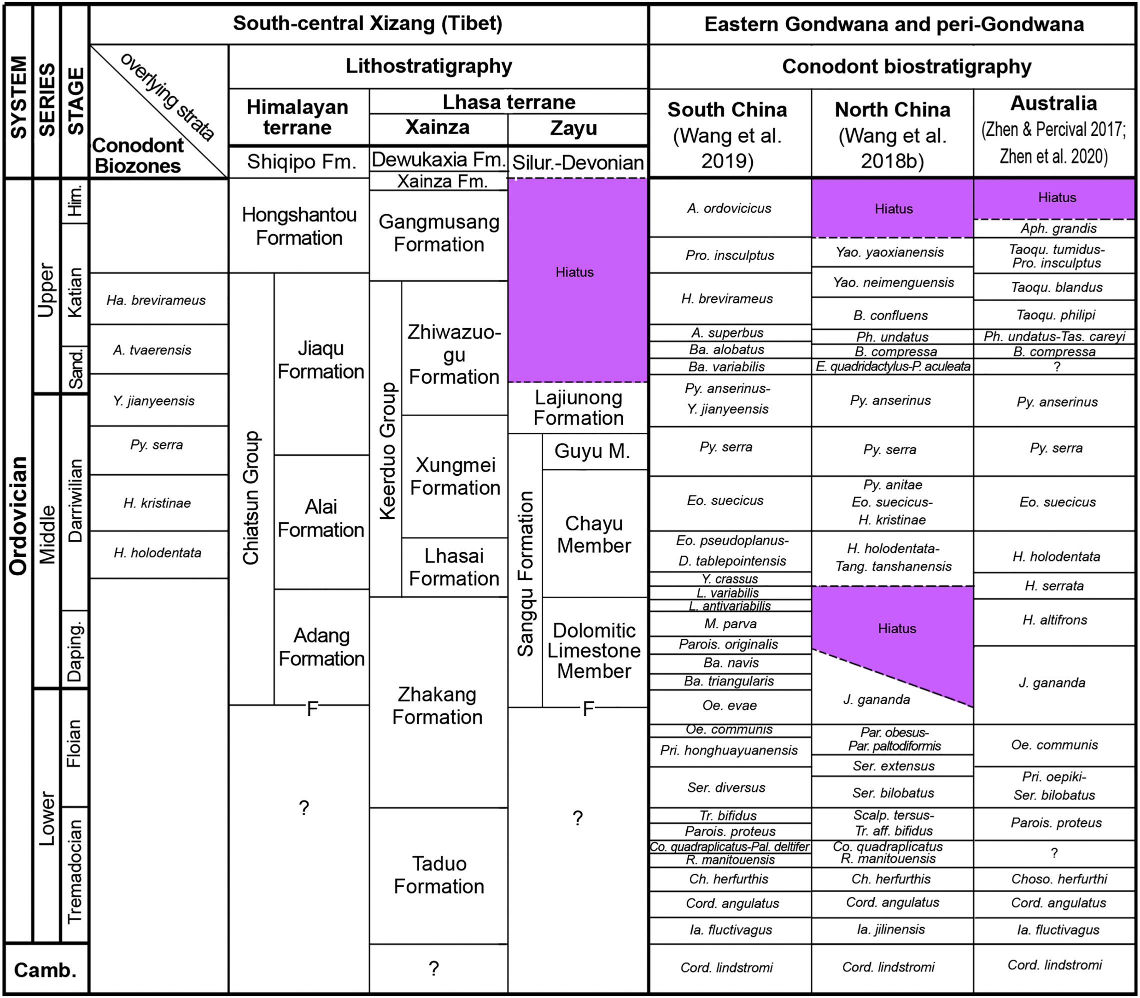

SYSTEM
SERIES
STAGE
Conodont Biozones
overlying strata
South-central Xizang (Tibet)
Lithostratigraphy
Himalayan terrane
Lhasa terrane
Xainza
Zayu
Shiqipo Fm.
Dewukaxia Fm.
Silur.-Devonian
Xainza Fm.
Eastern Gondwana and peri-Gondwana
Conodont biostratigraphy
South China (Wang et al. 2019)
North China (Wang et al. 2018b)
Australia (Zhen & Percival 2017; Zhen et al. 2020)
Ordovician
Upper
Middle
Lower
Him.
Katian
Sand.
Darriwilian
Daping.
Floian
Tremadocian
Camb.
Ha. brevirameus
A. tvaerensis
Y. jianyeensis
Py. serra
H. kristinae
H. holodentata
Hongshantou Formation
Chiatsun Group
Jiaqu Formation
Alai Formation
Adang Formation
F
?
Gangmusang Formation
Keerduo Group
Zhiwazuo-gu Formation
Xungmei Formation
Lhasai Formation
Zhakang Formation
Taduo Formation
?
Hiatus
Lajiunong Formation
Sangqu Formation
Guyu M.
Chayu Member
Dolomitic Limestone Member
F
?
A. ordovicicus
Pro. insculptus
H. brevirameus
A. superbus
Ba. alobatus
Ba. variabilis
Py. anserinus-Y. jianyeensis
Py. serra
Eo. suecicus
Eo. pseudoplanus-D. tablepointensis
Y. crassus
L. variabilis
L. antivariabilis
M. parva
Parois. originalis
Ba. navis
Ba. triangularis
Oe. evae
Oe. communis
Pri. honghuayuanensis
Ser. diversus
Tr. bifidus
Parois. proteus
Co. quadraplicatus-Pal. deltifer
R. manitouensis
Ch. herfurthis
Cord. angulatus
Ia. fluctivagus
Cord. lindstromi
Hiatus
Yao. yaoxianensis
Yao. neimenguensis
B. confluens
Ph. undatus
B. compressa
E. quadridactylus-P. aculeata
Py. anserinus
Py. serra
Py. anitae Eo. suecicus-H. kristinae
H. holodentata-Tang. tanshanensis
Hiatus
J. gananda
Par. obesus-Par. paltodiformis
Ser. extensus
Ser. bilobatus
Scalp. tersus-Tr. aff. bifidus
Co. quadraplicatus R. manitouensis
Ch. herfurthis
Cord. angulatus
Ia. jilinensis
Cord. lindstromi
Hiatus
Aph. grandis
Taoqu. tumidus-Pro. insculptus
Taoqu. blandus
Taoqu. philipi
Ph. undatus-Tas. careyi
B. compressa
?
Py. anserinus
Py. serra
Eo. suecicus
H. holodentata
H. serrata
H. altifrons
J. gananda
Oe. communis
Pri. oepiki-Ser. bilobatus
Parois. proteus
?
Choso. herfurthi
Cord. angulatus
Ia. fluctivagus
Cord. lindstromi

Figure 6

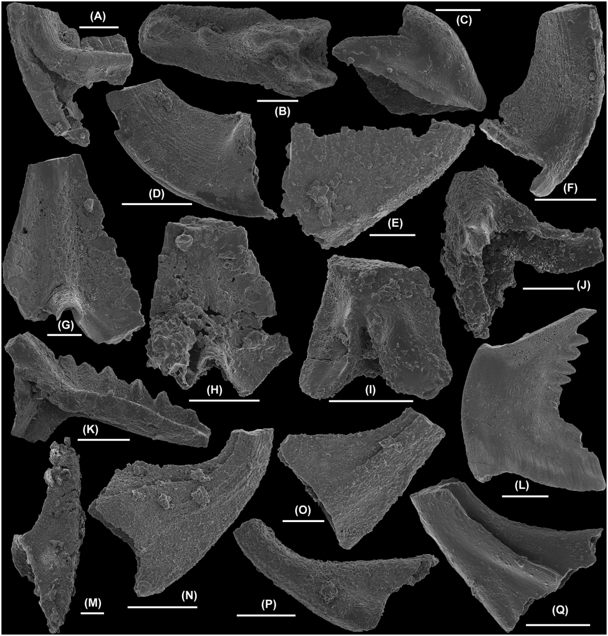


Figure 7

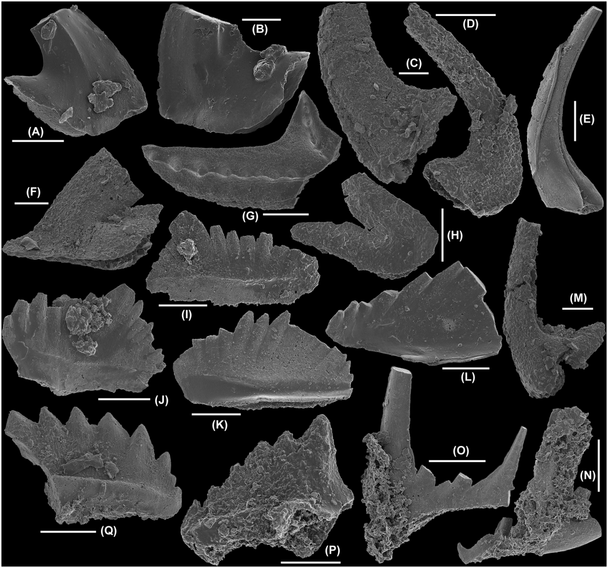


Figure 8

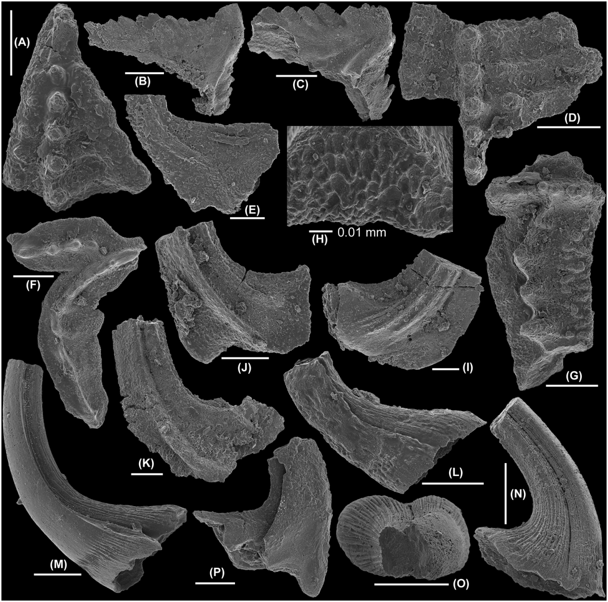


Figure 9

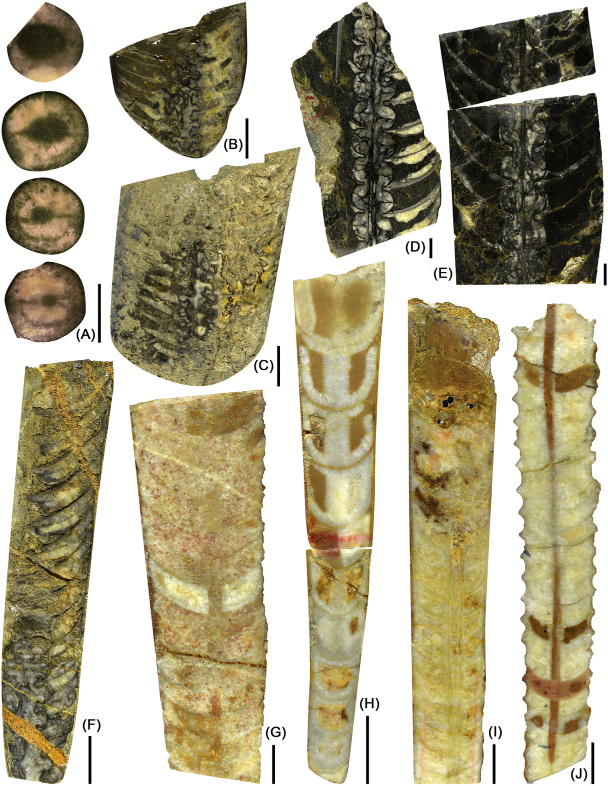


Figure 10

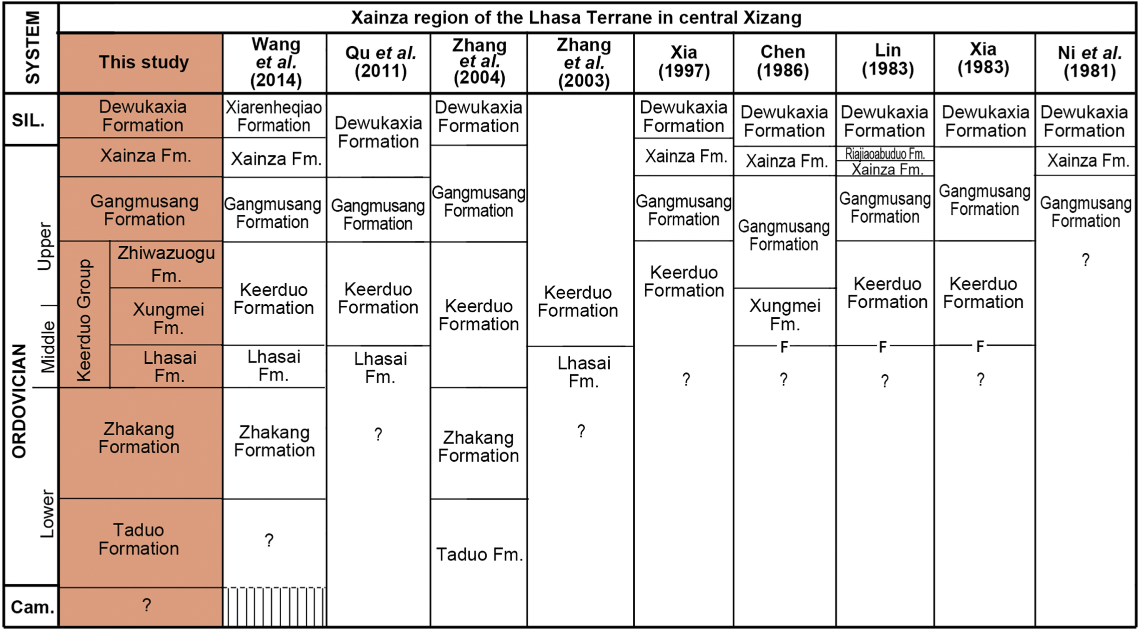

SYSTEM
Xainza region of the Lhasa Terrane in central Xizang
This study
Wang et al. (2014)
Qu et al. (2011)
Zhang et al. (2004)
Zhang et al. (2003)
Xia (1997)
Chen (1986)
Lin (1983)
Xia (1983)
Ni et al. (1981)
SIL.
ORDOVICIAN
Upper
Middle
Lower
Cam.
Dewukaxia Formation
Xainza Fm.
Gangmusang Formation
Keerduo Group
Zhiwazuogu Fm.
Xungmei Fm.
Lhasai Fm.
Zhakang Formation
Taduo Formation
?
Xiarenheqiao Formation
Xainza Fm.
Gangmusang Formation
Keerduo Formation
Lhasai Fm.
Zhakang Formation
?
Dewukaxia Formation
Gangmusang Formation
Keerduo Formation
Lhasai Fm.
?
Dewukaxia Formation
Gangmusang Formation
Keerduo Formation
Zhakang Formation
Taduo Fm.
Keerduo Formation
Lhasai Fm.
?
Dewukaxia Formation
Xainza Fm.
Gangmusang Formation
Keerduo Formation
?
Dewukaxia Formation
Xainza Fm.
Gangmusang Formation
Xungmei Fm.
F
?
Dewukaxia Formation
Riajiaoabuduo Fm.
Xainza Fm.
Gangmusang Formation
Keerduo Formation
F
?
Dewukaxia Formation
Gangmusang Formation
Keerduo Formation
F
?
Dewukaxia Formation
Xainza Fm.
Gangmusang Formation
?

Figure 11

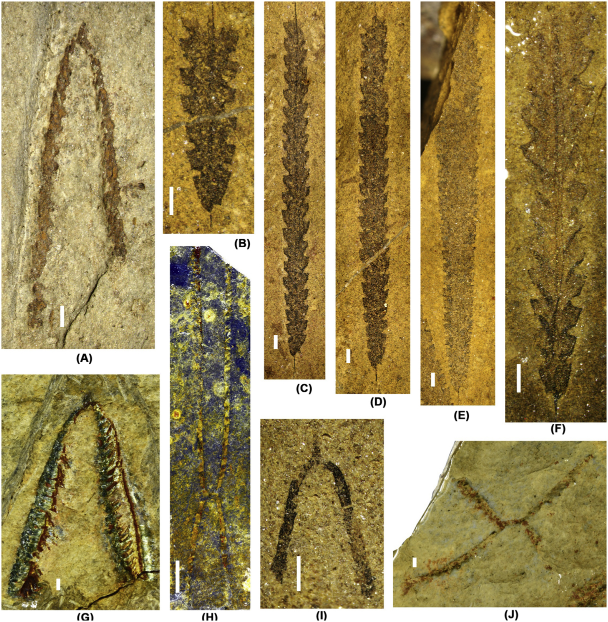


Figure 12